ASD TECHNICAL REPORT 61-236

ALKALINE BATTERY EVALUATION

I. F. Luke
W. G. Ingling
W. W. Clark

INLAND TESTING LABORATORIES
Cook Electric Company
Dayton, Ohio

Contract Nr AF33(616)7529

MAY 1961

FLIGHT ACCESSORIES LABORATORY
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICES

ASD TECHNICAL REPORT 61-236

ALKALINE BATTERY EVALUATION

I. F. Luke
W. G. Ingling
W. W. Clark

Inland Testing Laboratories
Cook Electric Company

May 1961

Flight Accessories Laboratory

Contract Nr AF33(616)7529

Project Nr 3145

Task Nr 61079-9

AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This report was prepared by Inland Testing Laboratories, Cook Electric Company, Dayton, Ohio, on Air Force Contract AF 33(616)-7529, under Task No. 61079-9 of Project No. 3145. This work was administered under the direction of the Static Energy Conversion Section, Flight Vehicle Power Branch Flight Accessories Laboratory, ASRMF, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. Acknowledgement is made of the assistance of Mr. J. E. Cooper, Task Engineer for the Flight Accessories Laboratory.

A technical report of all tests and results will be prepared and distributed by Cook Electric Company each six (6) months hereafter for the duration of the contract. The data, results, and conclusions from the work performed will be complete and current at the time of preparation. This report will be a progressive type which will contain all pertinent data contained in the previous reports.

This report covers work conducted from 30 June 1960 to 15 April 1961.

ABSTRACT

This report covers the first period of an alkaline battery applied research and failure analysis program. The purpose of this program is to establish a broad base of battery test data for use in the design of the electrical system of future space vehicles and to determine the actual failure mechanism of all new battery systems under varying environmental and cycle-life conditions so that improved space batteries can be developed. Another objective is to determine techniques and/or materials to prevent these failures while at the same time increase the usable watt-hours-per-pound capability and cycle life of the battery.

To date cycle-life tests have been conducted on one type of 12 ampere-hour, sealed, nickel-cadmium cell in two temperature environments and four depths of discharge.

Initial results in the program show that: (1) Cell cycle-life with shallow discharges is considerably longer than cycle-life at deep discharges and (2) Cycle-life is reduced by high ambient temperatures.

The program will include as future work evaluation of silver-cadmium and silver-zinc type cells.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or conclusions contained herein. It is published for the exchange and stimulation of ideas.

FOR THE COMMANDER:

George W. Sherman, Chief
Flight Vehicle Power Branch
Flight Accessories Laboratories

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

The complexities involved in operating a system in a space environment confronts the designers of space vehicles with a multitude of problems. One such problem is that of obtaining a highly reliable, long-life, power conversion unit, that will yield a maximum of energy per unit of weight. The most promising units for feasibly fulfilling these requirements are certain alkaline cells and batteries. The designer should have a wealth of information regarding the performance characteristics, particularly the probable useful life, of these cells when they are subjected to the various load conditions in the many temperature environments they may encounter in outer space. In addition to the need for information on the operating characteristics of existing cells, there is a need for knowledge of their failure mechanisms in order that corrective measures can be taken in the design and construction of new and better cells.

In one step toward satisfying the needs for information on cells and batteries for space applications, this evaluation program is currently being conducted on one type of 12 ampere-hour nickel-cadmium cells. This program is the only extensive, large-scale program of its kind known to have been undertaken to date, and is being expanded to include two other basic types of alkaline cells, namely silver-cadmium and silver-zinc, together with additional nickel-cadmium cells.

Manuscript released by the authors 29 May 1961
for publication as an ASD Technical Report.

II. DISCUSSION

A. Description of Test Cells and Batteries

The types of cells and batteries received to date for tests are sealed nickel-cadmium 12 ampere-hour (at the 2-1/2 hour rate) cells, Sonotone Part No. 22340 and packaged 20-cell batteries, Sonotone Part No. W-23217 (see figures 32 and 33).

The cell, Sonotone Part No. 22340, was originally designed for use in the Courier Satellite under a contract with Philco Corporation; however, the battery package comprised of these cells was specially built with 20 cells for this test program. However, the battery was not designed specially to withstand the particular test conditions. The cell manufacturer states that this cell was designed for shallow-discharge operation at temperatures from 60 to 90°F. A prime reason for selecting this particular cell rather than one specifically designed to withstand some of the more severe operating conditions was that this cell was an "off-the-shelf-item" and represented a practical, operational sealed nickel-cadmium cell. It was believed to be an initial good reference for obtaining data on the capability, cycle-life, and failure mechanisms of present cells.

The rated cell capacity was determined by the manufacturer to be 12 ampere-hours at a 2.5 hour discharge rate taken to a 1.0 volt per cell endpoint at 75°F.

The plates, both positive and negative, of the cell-core assembly have as their foundation a screen of nickel wire mesh which was converted into a plaque by sintering a carbonyl-nickel powder about the meshes. The positive and negative plates are distinguished by the active material which is electrochemically deposited within the pores. The positive plates were made by depositing nickel hydroxide, and the negative plates by depositing cadmium hydroxide. A nickel connecting tab is welded to one corner of each plate. In forming the core assembly, the plates are positioned such that the connecting tabs of all the positive plates project upward toward the positive terminal to which they are then simultaneously spot welded. Similarly, the tabs from the negative plates project upward near the opposite top edge of the cell and are spot welded to the negative terminal.

There are a total of 14 positive plates and 13 negative plates in each cell separated by a strip of regenerated cellulose which is slightly wider than the plates and interwoven between them. The plates are flat and each measures 2 inches by 3-1/2 inches, providing an effective plate area of 6.75 square inches per plate, after deducting the 0.25 square-inch area provided for the tab weld.

The portion of the terminal lug immediately above the tab weld has a square shank that is imbedded in a rectangular block of teflon which fits against three sides of the case and serves to prevent the lug from turning in the case as well as to insulate the lug from the top of the case. The terminal-to-case seal is effected by a teflon bushing expanded into a restraining cup by a nut-and-washer combination. The 3/16 inch threaded terminal lug extends through this bushing to the tabs.

The electrolyte consists of a solution of potassium hydroxide, approximately 30% by weight in distilled water, and is limited in quantity to that required to saturate the separator material, thus producing a "starved electrolyte" type of cell.

The entire core assembly is then wrapped by a 4-3/8 inch-wide strip of 0.005 inch nylon to insulate it from the sides of the metal cell case. The assembly is protected from shorting to the bottom of the case by a 0.031 inch plastic plate resting on the bottom.

The cell case is constructed of stainless steel sheet 0.022 inches thick welded to recessed plates at the top and bottom, and along one longitudinal corner of the cell. The cell case is 5 inches high, 2-1/8 inches wide and one inch thick. The complete cell assembly weighs approximately 511 grams (or 17.7 ounces).

The cell, Sonotone Part No. 22340, being a sealed cell for space applications, is provided with a high-pressure relief valve which is set at the factory to actuate at 200 psi ± 20 psi. The relief-valve assembly is screwed into the cell case midway between the two terminals and is sealed with a rubber "O-ring". The assembly may be removed and replaced without disturbing the calibrated actuation setting.

The twenty-cell battery case is constructed of 1/4 inch magnesium with a removable lid secured by twelve 1/4 inch stud bolts. The two battery leads and a grounding lead are brought through the battery case by means of a 3-pin electrical connector, Bendix Type PT02E-12-3S. The cells are arranged in two rows of ten each and are connected in series.

In order to test the batteries with the covers on the cases, which is required for proper restraining of the cells, the 3-pin electrical connector was removed from the end of each battery case to provide an exit for the many power, cell-voltage, and thermocouple leads.

B. Test Work Required under the Initial Program

The initial program called for the evaluation of 190 sealed nickel-cadmium cells and four 20-cell batteries, described in II-A, "Description of Test Cells and Batteries". The purpose of the program was to determine the cyclic-performance capabilities under specified temperature and load conditions.

Upon completion of preliminary tests to determine charging currents and maximum charging voltages to be used in the life tests, cycle-life tests are to be conducted at the following ambient test temperatures: -30°F, 0°F, 75°F and 120°F. A soak period of 24 hours would be allowed prior to beginning the life test cycles.

At each of the aforementioned ambient test temperatures, four 10-cell groups are to be cycled between the specified states of charge as follows:

One group cycled between full charge and 75% of full charge (25% discharge); one group between full charge and 50% of full charge (50% discharge); one group between full charge and 25% of full charge (75% discharge); and one group between 80% of full charge and 20% of full charge. The four 20-cell batteries are to be cycled at an ambient temperature of 75°F with one battery subjected to each of the above charge-discharge conditions.

All cycle-life tests are to be conducted with a 90-minute simulated-orbit period consisting of 55 minutes of charging and 35 minutes of discharging.

A summary of the test-cell distribution in terms of discharge depth, temperature environment, and grouping is shown in chart form in Table I. The 30 cells not listed on this chart are to be used for preliminary tests and as replacements for failed cells in the 20-cell batteries.

All discharges are specified as constant current rates and all charges are to be constant current up to the point at which the charging voltage reaches the maximum tolerable level that will not cause excessive gassing. Under the initial program, the tests were to continue for a minimum of 6000 cycles of charge and discharge. However, additional specified work provides for a minimum of 12,000 cycles or until the cell group fails in accordance with the criteria for failure as described in the following paragraphs.

NICKEL-CADMIUM

Orbit Period: 90 Minutes Charge: 55 Minutes Discharge: 35 Minutes

Test Units	CR* / Temp*	100% to 75%	100% to 50%	100% to 25%	80% to 20%
4 Cell Groups 10 Cells per Group	75°F	1 Group	1 Group	1 Group	1 Group
4 Cell Groups 10 Cells per Group	120°F	1 Group	1 Group	1 Group	1 Group
4 Cell Groups 10 Cells per Group	0°F	1 Group	1 Group	1 Group	1 Group
4 Cell Groups 10 Cells per Group	-30°F	1 Group	1 Group	1 Group	1 Group
4 Batteries 20 Cells per Battery	75°F	1 Battery	1 Battery	1 Battery	1 Battery

*CR Denotes Cycling Range in Terms of Percent of Full Charge
*Temp Denotes Temperature Environment

Table I Summary of Initial Test Program

The criteria for a cell to fail is that it is unable to deliver the required current on the test for a full discharge time (35 minutes). If a single cell fails or if some other defect arises in a single cell which is likely to damage the other cells in the group, the defective cell may be removed from the string and the charge and discharge conditions adjusted as necessary to maintain the charging conditions on the remainder of the cells.

If a cell failure occurs in a battery during the life test, the cell is to be electrically removed from the battery and replaced with a new cell, and the test continued.

Failure of one half of the original cells in a group or battery constitutes failure of that group or battery.

An analysis of each failed cell is to be made by the manufacturer to determine the cause (or causes) of failure and to make recommendations to minimize or eliminate the cause of failure.

The cells and batteries are to be cycled continuously, 24 hours per day, seven days per week.

Throughout all life tests, the terminal voltages of each cell, and the temperatures of three innermost cells of each group and battery are to be monitored and recorded periodically. The individual test cells are to be arranged in fixtures such that the ambient air is free to circulate between them, and proper restraining is provided to safeguard them from excessive internal pressures.

C. Instrumentation and Facilities

1. Environmental Chambers

There are four chambers required for the cell and battery evaluation program. The chambers for the 75°F and the 120°F tests were manufactured by Blue M Electric Co., Model Numbers POM-24 and POM-16. Cooling coils were added to these chambers to permit better temperature control. The differential temperature is controlled to within ±2°F from the desired temperature. The other two temperatures (-30°F and 0°F) are obtained from two low-temperature chambers which were modified to meet the test requirements. These two chambers are also controllable to within ±2°F.

These four chambers were selected so that the test items would comprise less than 1/3 of the internal volume, to assure adequate free circulation of ambient air.

2. Automatic Cycling Apparatus

Each group of ten cells and each battery has its own independent charge-discharge cycling equipment, except for a cycle timer and counter which is common to all units for that orbit period. A block diagram of the servo-controlled constant-current/constant voltage equipment is shown in figure 1. During the charging phase, the filtered output of a bridge rectifier is applied to the terminals of the test specimen. The charging current is sampled by the voltage drop across an instrument shunt. This voltage is then compared with a calibrated IR drop from a divider across a regulated, solid-state, constant-voltage source. Any differential voltage, which would represent a deviation in charging current, is then chopped in synchronism with the AC supply voltage. The phase of the resulting wave-form is either in phase or 180 degrees out of phase with the AC supply voltage, depending upon the polarity of the differential dc voltage, which is determined by the direction of current deviation from the desired constant-current value. The chopped "error" signal is voltage amplified and fed to grids of two power amplifiers whose plates are impressed with a 60-cycle voltage derived from the AC supply and center tapped between the plates to provide a 180-degree phase difference for the plates. One of these tubes will conduct, depending upon the phase relationship between the grid and plate signals. Since the plates are 180 degrees out of phase and the grids are in phase with respect to each other, the output of the power amplifiers is a pulsating DC, which is fed to a resonant circuit consisting of one winding of a two-phase servo motor and an external capacitor. The current in that winding is essentially sinusoidal and 90 degrees out of phase with the AC supply voltage. Whether the current leads or lags depends upon the polarity of the error signal. The other winding of the two-phase motor is excited by the AC supply voltage. Hence, mechanical rotation is produced to drive the current-correcting mechanisms until the error signal is reduced to zero and equilibrium is established.

If there is no deviation in battery current, there is no input signal to the power amplifier since there is no unbalanced DC voltage. Therefore, the grid potential is constant at some negative value determined by the bias, and the plate currents of the tubes are equal for each half-cycle period of operation. The servo motor is then torqued alternately in opposite directions at twice the AC supply frequency, thus producing no motion.

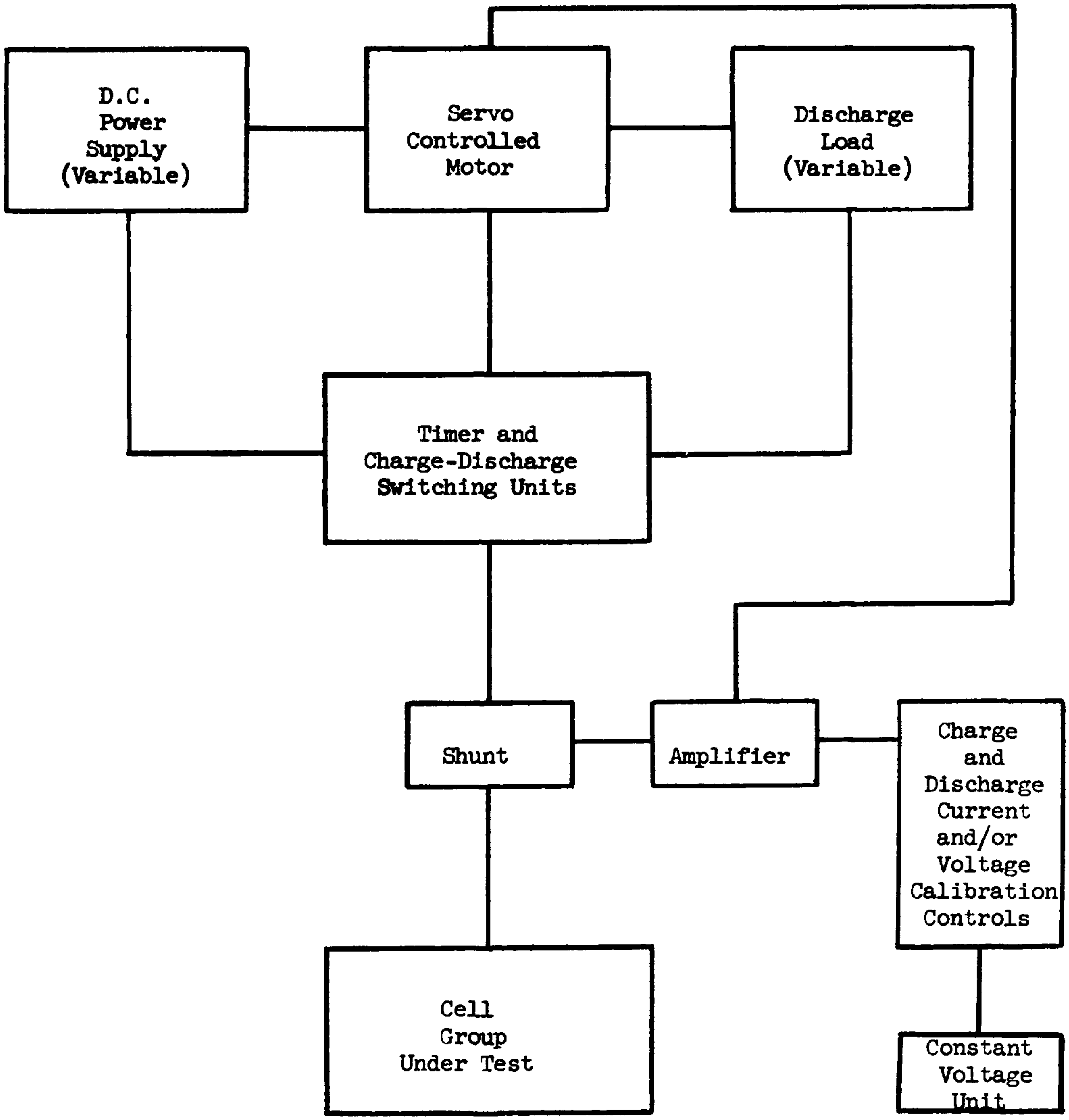

Figure 1 Block Diagram of Charge-Discharge Equipment

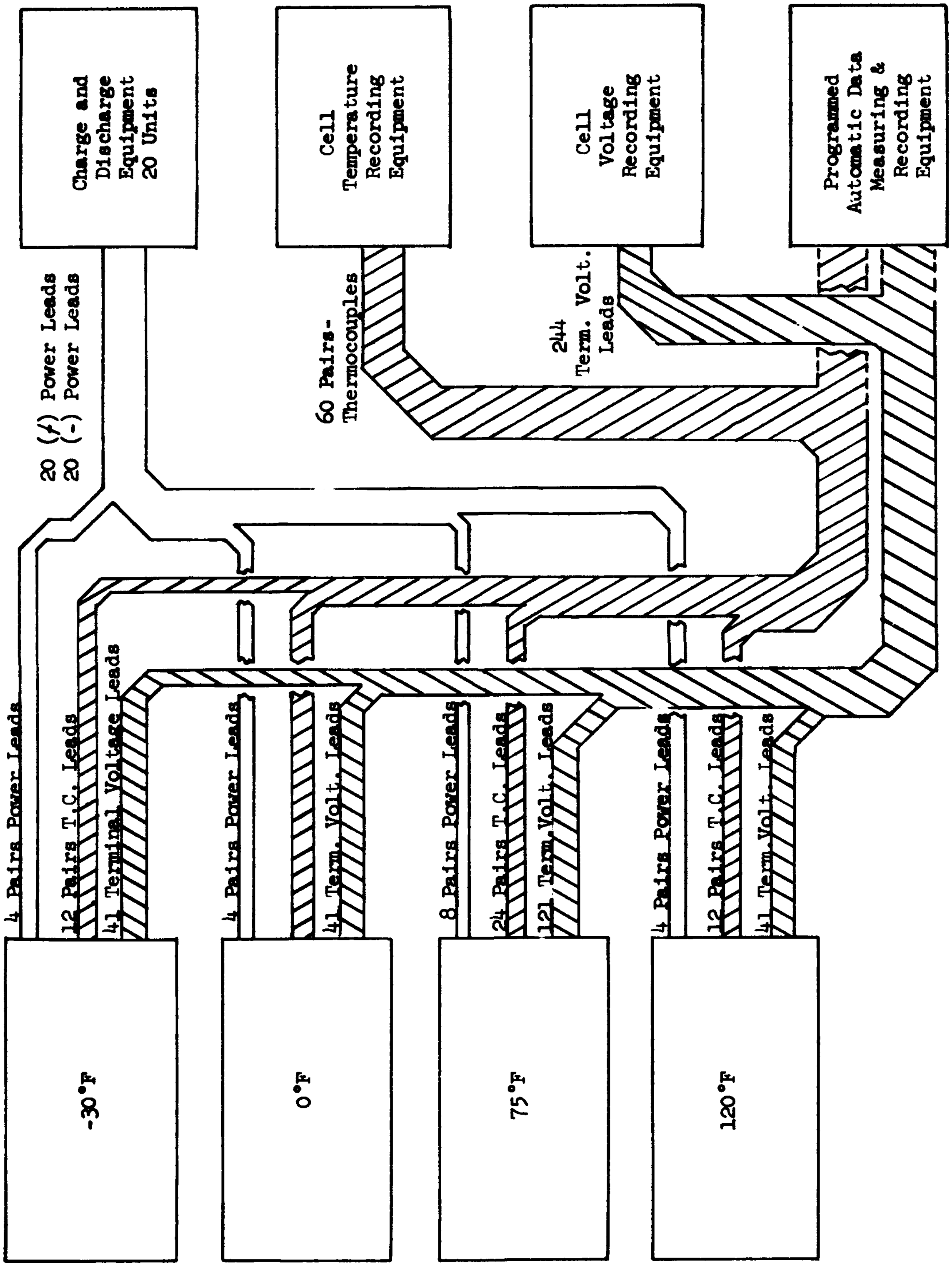

Figure 2 Interconnecting Cable Layout for Initial Program Instrumentation.

As the charging phase continues at constant current the charging voltage sometimes reaches a level above which excessive cell gassing is likely to occur that could endanger the cell. Once this critical voltage level has been determined, a calibrating potentiometer can be pre-set such that a sensitive relay across the output terminals of the charger will be energized at that level, causing the equipment to switch from a constant-current mode of charging to a constant-voltage mode. Obviously, during the constant-voltage mode the current adapts itself to the battery conditions. The voltage level at which the charger will control can be pre-set with a calibrating potentiometer across the constant-voltage unit. The over-all terminal voltage of the test cell group or test battery is sampled from a high-resistance voltage divider directly across the battery terminals to avoid error introduced by charging currents during the constant-voltage mode of operation. The sample of terminal voltage is compared with a pre-set reference voltage picked off by the calibrating potentiometer divider across the constant-voltage unit. At the time of the mode change, appropriate switching by relays disconnect the instrument shunt and connect the shunt divider as the terminal voltage and the reference is processed the same as in the constant-current mode.

In either charging mode, the error-correcting device is a variable autotransformer mechanically coupled to the servo motor.

In the discharge phase, the instrument shunt again serves as the current sensor but the reference is a third divider voltage from the constant-voltage unit and is preset to correspond to the desired discharge current. The error correcting device for the discharge phase is a high-wattage rheostat which is also mechanically coupled to the servo motor.

3. Data Recording Instruments

Voltage - The individual cell voltages were initially monitored by a 16-channel strip-chart recorder, Minneapolis-Honeywell, Model No. 153X64V16-X-41. The various cell voltages are first fed into a multiplexing system and then to a calibration network before going to the recorder itself. This recorder prints once every five seconds. The range of this instrument is zero (0) to + two (2) volts and is graduated in hundredths of a volt.

Temperature - The temperatures of the cells were monitored via copper-constantan thermocouples and are being recorded on a 24-channel strip-chart recorder, Daystrom, Inc., Model No. 6702. This recorder prints once every three seconds. The scale range of this instrument is -50°, +0, +150°F and is graduated in degrees.

Automatic Data Handling Units - An automatic data processing system has been installed to more adequately handle the mass data involved. Both voltages and temperatures will be measured, converted into digital form, and permanently recorded on tape and/or punch-cards. These punch-cards then will be ready for computer processing, which will offer flexibility in recalling and correlating any combination of recorded functions at any time. The measuring consoles consist of scanner stepping switches which introduce, successively, test functions into a programmed test circuit at the rate of one function per second. A digital voltmeter then converts this information from analog-to-digital form and feeds the converted information into a Programmatic Flexowriter, Friden, Model SPD. The Flexowriter then converts the digitized data into punched-tape form. (See Section II, D "Data Collection and Processing").

4. Cell Connections for Test

Individual cells for life-cycle testing were assembled in groups of ten cells and electrically connected in series. The batteries are being tested as they were received (20 cells in series). Each cell voltage can be monitored independently. Each group of ten cells and each battery has three thermocouples placed in such a manner as to be representative of the group. Two brass washers were silver soldered together and the thermocouple was soldered in a small hole which was drilled between the washers. These washers were then placed on one of the cells' terminals and screwed down tightly along with the other wiring.

5. Thermocouple Reference-Junction Temperature Control

All thermocouples from the cells have been brought to terminal strips in a controlled temperature oven, and the reference junction is made at this point. The oven is thermostatically controlled and maintained at a temperature of 90°F ± 1°F.

6. Preparation of Cells for Testing

Upon receipt each cell was identified by affixing a small adhesive backed label on both the top and bottom of the cell.

Adhesive backed one-piece Mylar sheets having a thickness of two thousandths of an inch were placed around all four sides and bottom of each individual cell. The Mylar serves to isolate each cell electrically from the fixture to prevent circulating currents resulting from cell-to-case potentials.

The individual cells were placed in restraining fixtures accommodating ten series-connected cells each (1 group). These fixtures do not subject the cells to any initial pressure, but restrain them from deforming as a result of internal pressures with values below that required for normal operation of the cell relief valves. The restraining plates consist of one-quarter inch aluminum plates, four per cell, making full-area contact on the four sides of each cell. The tops and bottoms of the cells have no external restraining. The fixtures also provide for adequate thermal isolation among the cells, and free circulation of ambient air about each cell as specified.

One group of cells used in preliminary tests was prepared to provide monitoring of internal cell pressures by the removal of the complete relief-valve assembly of each cell and a 0 to 300 psi pressure gauge inserted in its place.

D. Data Collection and Processing

When received, each cell and battery was assigned identification symbols for entry into corresponding record books. One record book is a chronological diary of test activity, with proper reference to dates, time of day, cycle numbers, environmental and other test conditions, associated record charts, and instruments and personnel involved. Another record book is a ledger-type record of individual cells, cell groups, and batteries. This type of double-entry record-keeping has proved to be valuable in data analysis and retrospect.

At the outset of the program, in order to get cycle-life tests initiated as soon as possible, data was collected on strip-chart recorders as described in II, C, "Instrumentation and Facilities". The strip-chart rolls were then placed on scroll-type manual-readout devices, where the data was interpreted, and tabulated onto data sheets from which graphs of functions were plotted at representative cycles to depict the cell-group performance vs. cycles. However, since this procedure is laborious and time consuming, an automatic data-handling system was established wherein the various parameters are measured, converted into digital form, and permanently recorded on punched paper tape, and subsequently punch-cards.

This form of data storage lends itself readily to machine and computer processing. Consequently, the record cards can also be duplicated and analyzed by other qualified and interested agencies having access to computer facilities. The flexibility offered in recalling and correlating any combination of recorded functions at any time is a highly desirable feature because the full significance of a parameter or its relationship to some other parameter may not be appreciated, or of concern, until a considerably later date at which time it would be difficult, and perhaps too late, to feasibly make a particular analysis by the usual methods.

The measuring consoles are equipped with scanner stepping switches which introduce test functions (presently individual cell voltages and temperature-rise above ambient) sequentially into a programmed test circuit at the rate of one function per second. A digital voltmeter provides automated quantizing of a stable reference voltage. The quantizing action is accomplished by means of precision resistors selected by amplifier-driven stepping switches. Its purpose is to cause a selected portion of the reference voltage in a bridge circuit to equal an attenuated version of the unknown input voltage from a test cell or a thermocouple. Parallel contact closures on the stepper switches cause lamps to light in the digital readout display, providing a direct-reading indication of the measurement. When the bridge is in balance, a print control circuit locks the bridge at the measurement reading and provides a print-out control signal which is fed to a Flexowriter. The Flexowriter converts the quantized electrical input into punched-tape form from which a tabulated, alpha-numeric, coded print-out can be made on paper within seconds.

The data on the punched tape is then punched into tabular cards for use in a computer which correlates and otherwise processes data in accordance with a predetermined program.

E. Preliminary Tests

1. Establishing the Discharge Currents

The discharge currents were calculated for each of the required depths of discharge listed in II, B, "Test Work Required under the Initial Program", using the manufacturer's rated ampere-hour capacity of the cells at room temperature. (12 ampere-hours, determined at a 2.5 hour rate to a 1.0 volt-per-cell end point).

The 35-minute constant discharge current used in cycling the cells between 100% of full charge and 75% of full charge (25% depth of discharge) was computed as follows using the foregoing capacity rating:

$$\text{Discharge Amperes} = \frac{\text{12 Amp.-hours (rated capacity)} \times 25\%}{\left(\frac{35}{60}\right)\text{hours}} = 5.14 \text{ amp.}$$

Similarly, the discharge currents for the other depths of discharge were computed to be:

50% discharge, 10.29 amperes
75% discharge, 15.43 amperes
60% discharge, 12.34 amperes (used in the 80% to 20% of-full-charge cycling range)

2. Establishing the Maximum Charging Voltage

Since the test cells are sealed nickel-cadmium cells it is important to prevent excessive gassing from developing within the cell. In addition to the dangers resulting from exploded cells, which could jeopardize other equipment as well as other cells, excessive gassing can cause additional temperature rise of the cell, thereby reducing its life as a result of accelerated degradation of the separator material, particularly with cellulose-type (paper) separators. It is commonly known that excessive gassing can occur during charging as a result of the electrolysis of the water in the electrolyte. In this process oxygen is liberated at the positive plates and hydrogen at the negative plates. The oxygen recombines readily but the hydrogen is virtually unresponsive to recombination and is the major contributor to gas pressure build-up. The point at which considerable gassing begins is determined by voltage (approximately 1.46 volts per cell at room temperature) but the quantity of gas evolved depends upon the portion of the current that does not contribute to the charge of the battery. Hence, the gassing is most prevalent during the final portion of the charge period where the charging efficiency is lower, and higher applied voltages are required to overcome the increased EMF and internal resistance in the process of maintaining constant current.

To protect the cells from excessive gassing derived from high terminal voltages, it was found that upon reaching a given voltage level it was necessary to discontinue the constant-current mode of charging and to limit the charging voltage for the duration of the charge period.

Since the cells are being charged in series, the only controllable voltage is that applied to the series group. The voltage levels established to protect cells were based upon experimental results of pressures developed in relatively new cells where the distribution of voltage drop was practically uniform. However, it was later found as cells progressed through life-cycling tests, the internal resistance of the cells did not increase uniformly, thus causing a redistribution of the applied charging voltage to the group to the extent that some cells had high terminal voltages whereas others had quite sub-normal voltages (while the maximum voltage applied to the 10-cell group was not exceeded).

In an experiment designed to discover any relationship of cell-pressure build-up with charging conditions, no definite pattern was found that consistently showed a correlation of pressure with either charging current, cycle number, or group terminal voltage. However, in general, high charging voltages resulted in relatively higher pressures, several charge-discharge cycles would be required for an appreciable pressure build-up to be indicated (above 5 psig), the indicated pressure levels were different among cells, and the indicated pressures increased at different and variable rates. The tests also indicated that there was a higher incidence of relatively high pressures developed at 120°F than at 75°F for corresponding group voltages.

As a result of the experimentation with pressure-voltage relations, the maximum voltage levels for each 10-cell group used in life-cycling tests were set at 16.5 volts for tests at 75°F and 15.5 volts for tests at 120°F. As cells failed and were removed from tests, the overall voltage applied to the remaining cells was adjusted to maintain the same average voltage per cell.

3. Establishing the Charging Currents

The charging currents used in cycling the test cell groups and batteries were determined after a study of the ampere-hour efficiencies. The ampere-hour efficiency is defined by the Standardization Rules of the American Institute of Electrical Engineers as follows: "36-301, Ampere-hour Efficiency (Electro-chemical Efficiency). The ratio of the ampere-hours output to the ampere-hours of the recharge".

A general expression for the ampere-hours discharged by a battery for a period of time t, is given by the integral $\int_0^{t_d} I_d \, dt$

where I_d = discharge current and t_d = discharge time. Similarly, the total ampere-hours of charge passing through the battery during charging is $\int_o^{t_c} I_c \, dt$ where: I_c = charging current, and t_c = charge time. The ampere-hour efficiency in accordance with the foregoing definition is the ratio of these two integrals:

$$\text{Ampere-Hour Efficiency} = \frac{\int_o^{t_d} I_d \, dt}{\int_o^{t_c} I_c \, dt}$$

For both constant-current charging and discharging as are specified for this program, the expression for ampere-hour efficiency reduces to the simple ratio: $\frac{I_d \; td}{I_c \; tc}$

Another expression for the efficiency of storage batteries is the watt-hour or energy efficiency, which is defined by the AIEE as "the ratio of the watt-hours output to the watt-hours of the recharge" and is expressed as the ratio of two energy integrals:

$$\text{Energy Efficiency} = \frac{\int_o^{t_d} V_{td} \; I_d \; dt}{\int_o^{t_c} V_{tc} \; I_d \; dt} \qquad \text{where:}$$

V_{td} = Terminal voltage on discharge and,

V_{tc} = Terminal voltage on charge

This expression for efficiency involves all energy exchanges in the cell including heat losses, etc., and is valuable for design and development considerations. However, for the purposes of establishing charging currents only, the ampere-hour efficiency need be considered.

Since the terminal voltage-internal pressure relationship obtained experimentally indicated that the charging voltage would have to be limited to prevent excessive gassing, it became obvious that the charging current could not at all times be maintained at a constant value throughout the charge period. After the maximum voltage level is reached and maintained, the charging current decreases exponentially. This phenomena is illustrated in figure 4. During the constant-voltage mode of charging the ampere-hour accounting is greatly complicated, requiring a current-time integration during this period as follows:

$$\text{Ampere-hours during constant-voltage} = \int_{t_1}^{t_2} I_c \, dt$$

where: T_1 = time of switchover, and t_2 = time at end of charge period.

The total reinserted ampere-hours would then become:

$$\text{AH charge} = I_c t_1 + \int_{t_1}^{t_2} I_c \, dt$$

The preliminary cycling tests indicated that the elapsed charging time prior to switchover to the constant-voltage mode of charging varied considerably from cycle to cycle and was unpredictable -- sometimes the voltage limit was never reached during a cycle. Consequently, the ampere-hours re-inserted into the cells likewise was variable and inpredictable. Since the conditions for life tests were to be established and maintained throughout the tests regardless of changes in efficiency, and in view of the fact that the charging currents used in the preliminary tests were adequate to restore the corresponding cell groups to full charge, and yet provide no indication of excessive overcharging, these values were not altered for the life tests. These currents are listed as follows:

25% discharge	recharge at 4.25 amperes
50% discharge	recharge at 8.50 amperes
75% discharge	recharge at 12.75 amperes
60% discharge *	recharge at 10.20 amperes

* 80% to 20% of full charge

4. Special Tests

Prior to conducting cycle-life tests, certain preliminary tests were required to determine the optimum charging conditions. For these tests, 30 of the original 190 individual cells were provided in the program. Some of these cells will also be available as replacements for failed cells in the packaged 20-cell batteries.

The preliminary tests were begun on one group of ten series-connected cells equipped with individual pressure gauges and thermocouples, and mounted in a restraining fixture as described in II, C. 6. This group was first placed in the 75°F chamber and subjected to a slow charge of two amperes for eight hours to reasonably assure that full charge was attained. For the first test, the maximum-voltage

control was set to enable the voltage to rise to the anticipated point of excessive cell gassing. At the two-ampere rate no pressure was noted on any of the gauges until seven hours and ten minutes had elapsed. (The gauges do not indicate pressures below 5 psi). At this time one cell indicated approximately 6 psi with a terminal voltage of 1.57 volts. Shortly thereafter, other cells began indicating pressures with corresponding terminal voltages ranging from 1.54 to 1.57 volts. At the end of eight hours the charger was turned off and the cell pressures began dropping. After 28 minutes all pressures were below 5 psi. The behavior of cell pressures during the preliminary tests is described in II. E.2.

The charging currents used in the initial tests were based upon a cell efficiency factor of 77%, which provides for a return of 130% of the discharged ampere-hours if constant current can be maintained throughout the charging phase. After several cycles using currents based upon the foregoing efficiency factor, a capacity check was made which showed that the efficiency factor was suitable. Several other cycles were made using each of several values of current above and below those calculated. Again, capacity checks were made following each group of cycles. None of the values selected improved the recharge performance above that using the calculated currents. The same procedure was followed for cycling in the other three discharge-depth conditions.

The same group of cells equipped with the same instrumentation was placed in the 120°F chamber and soaked 24 hours prior to the start of tests. In this environment the cells were cycled and checked by the same procedure as used in the 75°F environment. These test results indicated no need for altering the current values used.

Following the tests at 120°F, the same cell group was placed in the -30°F environment and soaked for 2-1/2 days with the cells wired in parallel to allow the cell voltages to equalize prior to cycling. In the first attempt to charge the group at -30°F, it was found that the internal resistance of the cells was so great that a voltage in excess of 18.5 volts was required in order to attain a charging current greater than 1.0 amperes during the early portion of the test. Therefore, 1.0 ampere was used for 3 hours, at which time current regulation could no longer be maintained within the voltage limit. The constant-current level was then reset for 0.5 amperes where it was held for 5.25 hours. Thereafter, the current tapered off gradually to the extent that it became evident that over 70 hours of charging would be required to re-insert the required ampere-hours to restore full charge.

A shallow discharge at 2 amperes was attempted after 13.1 ampere-hours of recharge. After less than 4 ampere-hours were removed, one cell reversed polarity. Within minutes, several more cells went negative, and the test was ended.

Tests were then started at 0°F following the usual thermal stabilizing of the cells. The same procedure was used as in the tests at -30°F, that is, the initial current of 2.0 amperes was reduced incrementally as the limiting voltage was reached. After 17 ampere-hours had been inserted, a two-ampere discharge was begun. A graphic comparison of typical 2-ampere discharges at 0°F and -30°F are shown in Figure 3. This graph shows the reduced discharge capability of the cells at -30°F. The wide separation of the curves, particularly at the beginning of discharge, indicates the increased voltage drop resulting from higher internal resistance.

Since all the previous tests performed at 0°F and -30°F indicated that the cells could not meet the discharge performance requirements using constant current charging within normal charging voltage limits, it was decided to conduct a test using the specified cycle times with 25% discharges at 0°F with charging conditions chosen to re-insert the maximum possible charge within the limits of a maximum voltage of 15.0 volts for a ten-cell group, and a maximum current of 15 amperes. The re-inserted ampere-hours were determined by integrating the area under the current-versus-time curves for ten cycles each of two groups of cells. The average charge re-inserted was 2.49 and 2.75 ampere-hours respectively -- both short of the 3 ampere-hours required for best conditions. The ampere-hours of useful discharge obtained from these same cell groups during cycling at no time exceeded 2.75 and 1.72 ampere-hours respectfully, and averaged considerably less.

Next, a similar test was performed with the exception of using a higher maximum voltage of 16.0 volts. The results showed consistently satisfactory discharges for the 25% discharges used. Figure 5 shows a typical discharge curve obtained during the cycling.

Having achieved useful 25% discharges for 22 consecutive cycles at 0°F using a constant-voltage charger at 16.0 volts per group, cycles with 4.25 ampere constant-current charges were made at 0°F with the group terminal voltage limited to 18.2 volts. The 4.25 amperes represents the current that will re-insert 130% of the discharge ampere-hours in a 55-minute charge period following a 3 ampere-hour discharge. It was found that the maximum voltage

level was reached approximately half way through the 55-minute charge period, as shown in Figure 6, at which point the charger switched to a constant-voltage mode of operation, maintaining 18.2 volts on the cell group for the duration of the charge period. No indications of excessive gassing were noted.

The discharge voltage characteristics (see Figure 3 for a typical curve) were comparable with the 16.0 volts-per-cell-group constant-voltage charges, i.e., relatively flat with no indications of a "drop off" at the end of discharge, where the voltage consistently was in the vicinity of 1.18 volts per cell. The described tests indicate that the cells can be life-cycled using the hybrid charging method of part constant-current and part constant-voltage. However, since no evidence of excessive gassing was noted, additional tests were conducted to further explore the possibility of achieving a wholly constant-current charge by raising the maximum voltage level. Another test was then performed on the same group of cells under the same conditions except that the voltage applied to the group was limited to 19.0 volts. The charge characteristics were very similar to those with the 18.2 volt limit except that the switchover from constant-current charging to constant-voltage charging occurred approximately two-thirds of the way through the charging phase. Again, no evidence of excessive gassing was detected. Therefore, it is planned that further tests will be conducted at even higher maximum voltage levels prior to starting cycle-life tests on cells at 0°F.

F. Cycle-Life Tests

After conducting preliminary tests at ambient temperatures of 75°F and +120°F, eight groups of cells, not subjected to any previous tests, were prepared for life cycling. Four of these groups were placed in the 75°F chamber, and four in the +120°F chamber, and allowed to "soak" for 24 hours at the respective ambient temperatures to attain thermal stabilization prior to cycling. An initial charge of two amperes was applied to each group for a period of eight hours whereupon discharges were immediately initiated at the previously calculated rates described in II, E.1 "Establishing Discharge Currents". At the end of the specified 35-minute discharge period, the automatic cycling equipment switches to the charging mode of operation. Immediately, the constant-current regulation was checked on each of the eight chargers. Toward the end of the charge period the charging voltage for each group was monitored and maximum-voltage controls were set on each charger. Thereafter, the cycling operation continued automatically.

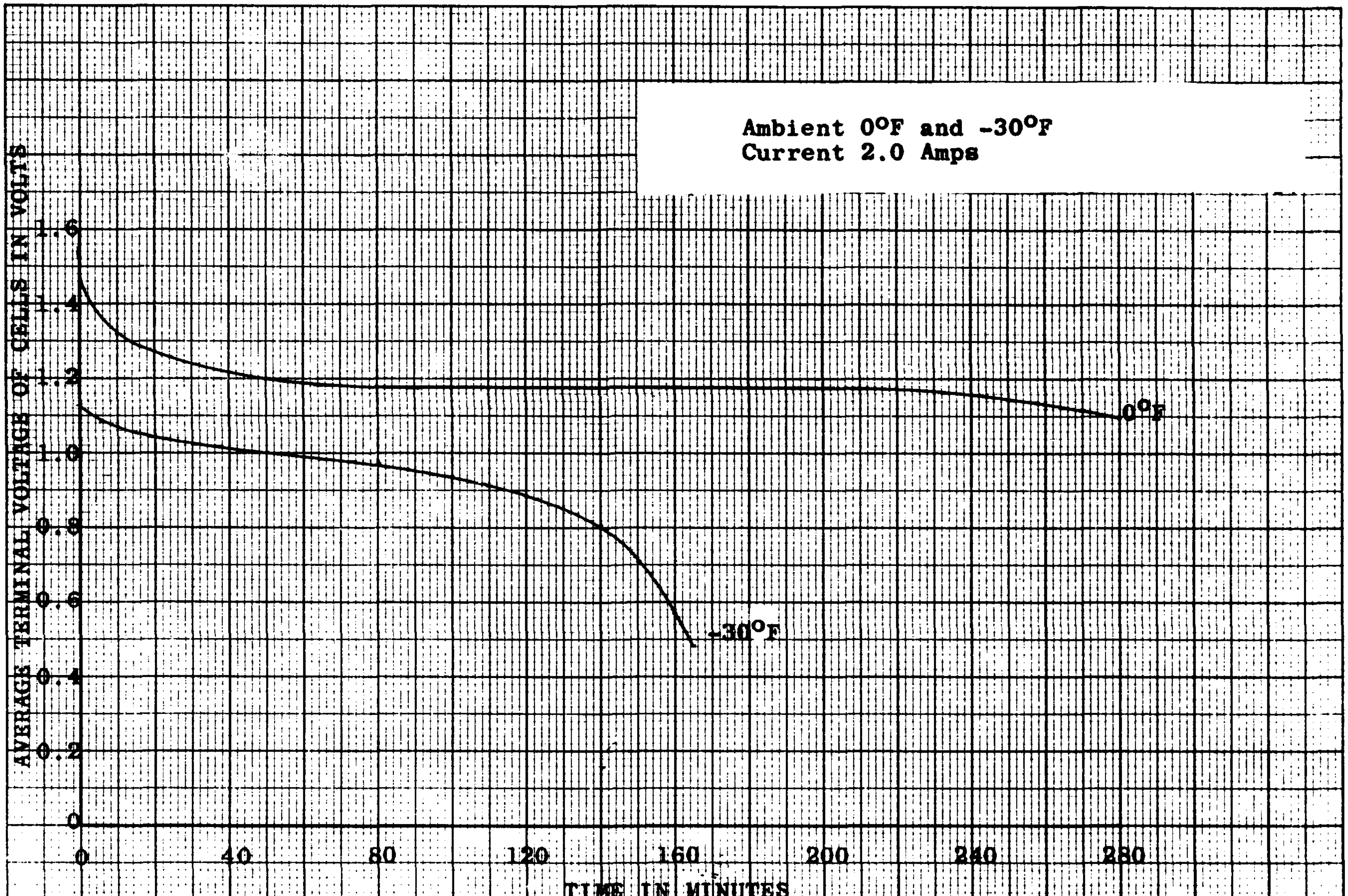

Figure 3 - Comparison of Typical Discharge Characteristics at $0^{\circ}F$ and $-30^{\circ}F$

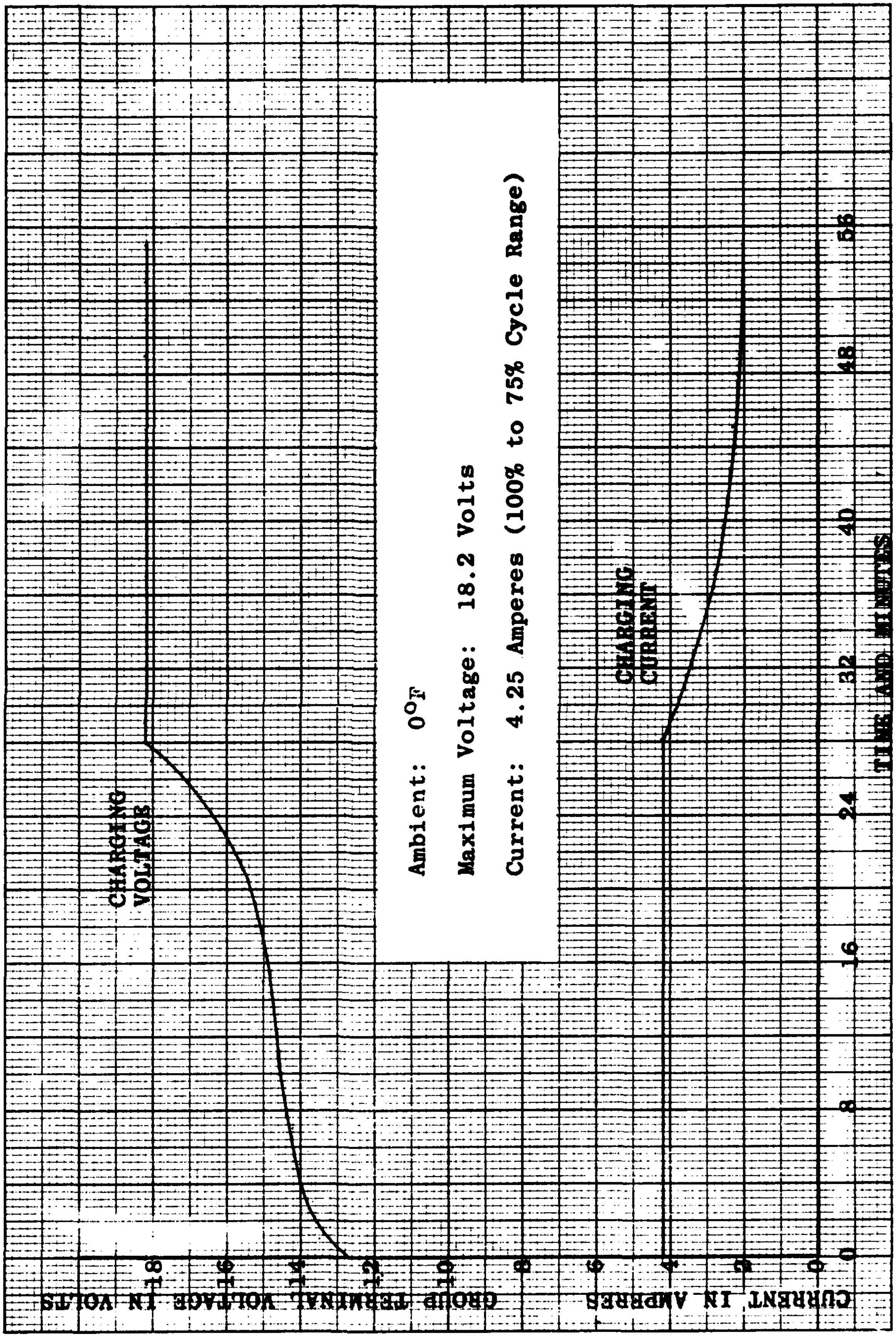

Figure 4 - Typical Charging Characteristic - Preliminary Test Group

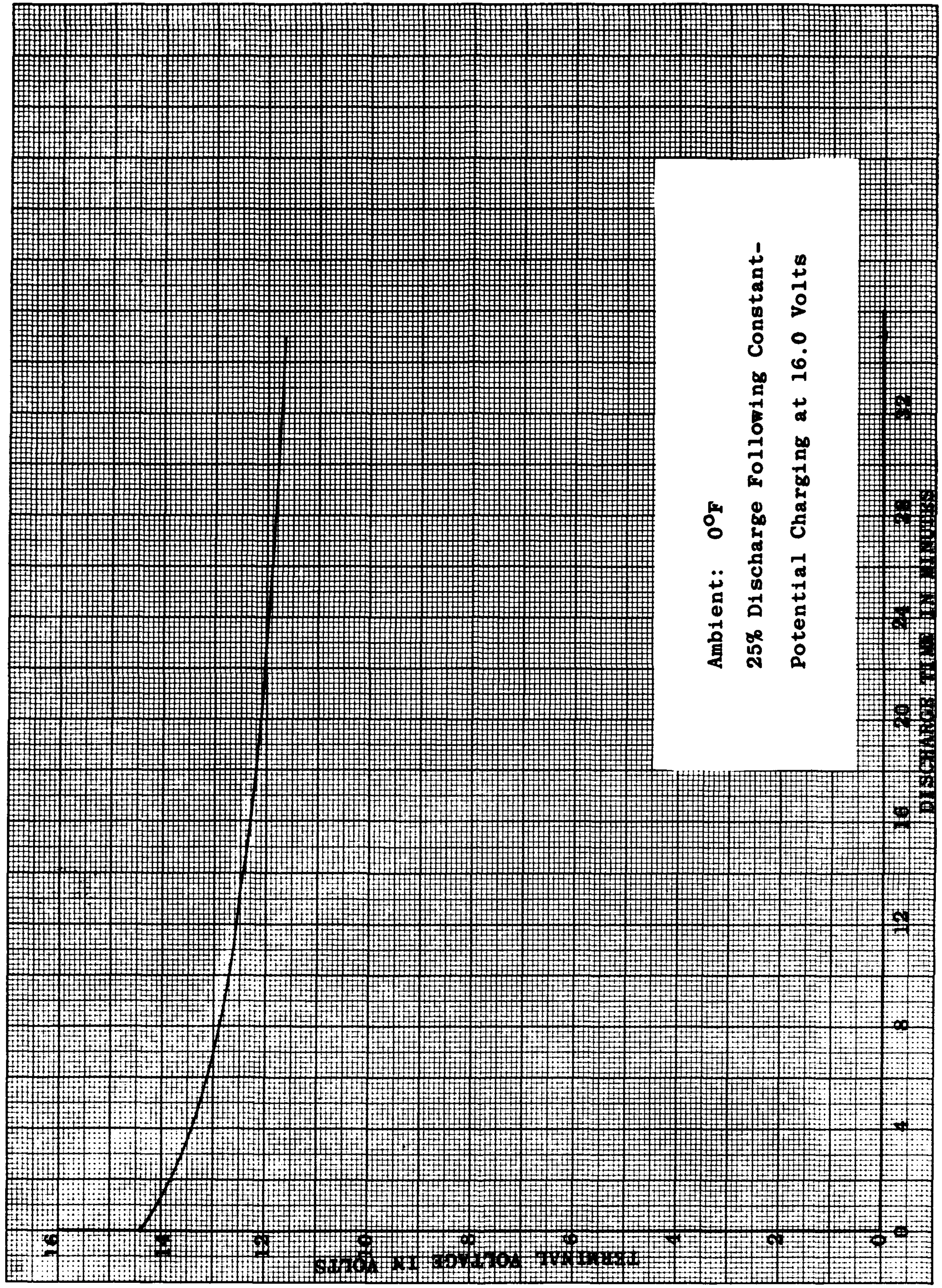

Figure 5 - Typical Discharge Characteristic, Ambient $0^{o}F$

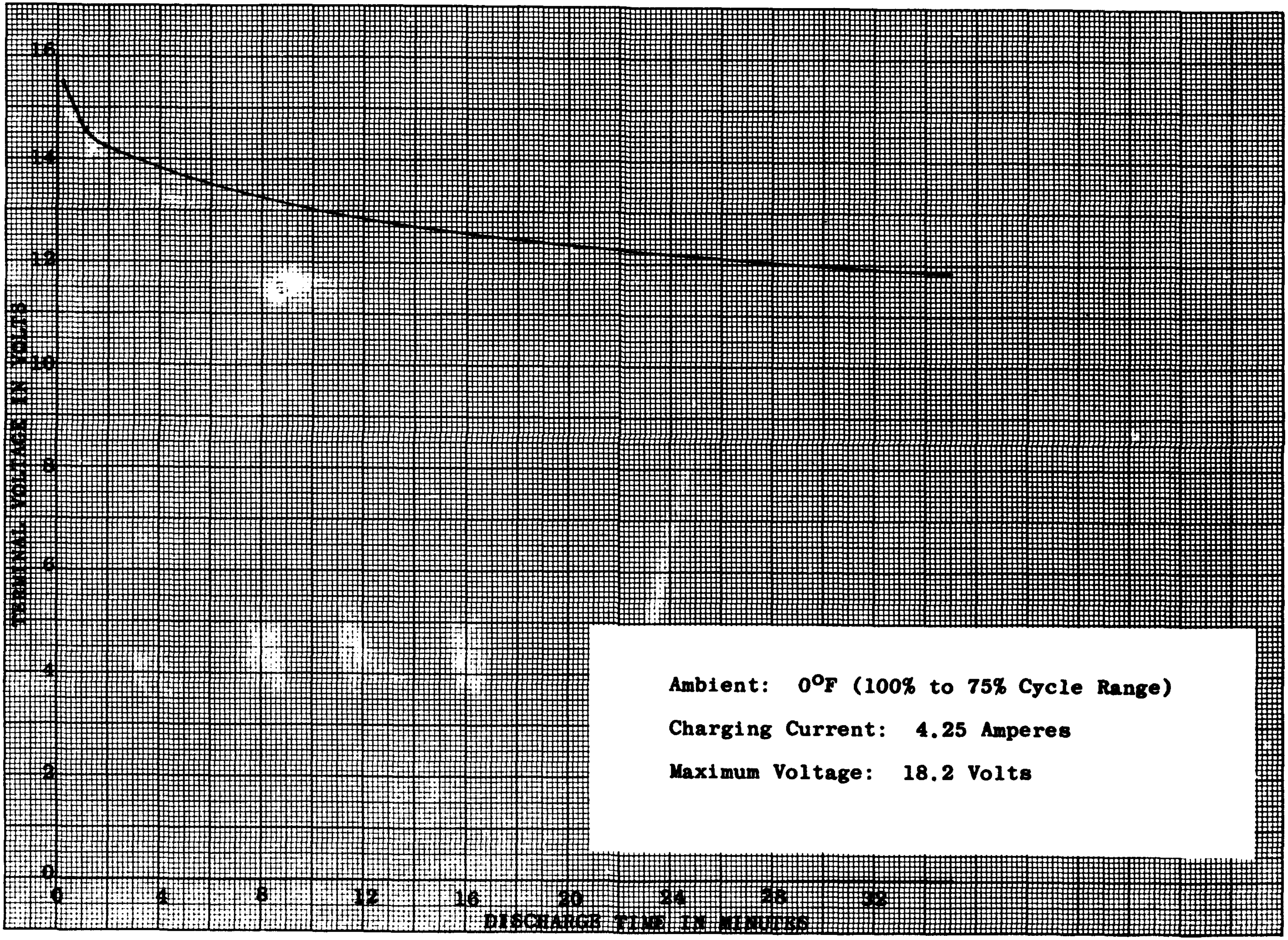

Figure 6 - Typical Discharge Characteristic, Ambient 0°F

During the life-cycling tests the terminal voltage of each cell was monitored from the strip-chart recorder. As indications of cell failures appeared, close observations were made of those particular cells in order to remove them electrically from the test group as soon as a failure occurred. In accordance with the specified criteria for failure, a low terminal voltage in itself, was not considered as a reason for failure until it reached zero. The criteria stipulated that for a cell to fail it must be unable to deliver the required current for a full discharge time. It was therefore assumed that the cell was contributing to the series current as long as its terminal voltage remained positive. However, if the required current of a group could not be maintained with all cell voltages positive, the cell with the lowest terminal voltage was removed. This process continued, as necessary, to maintain the required discharge current for the group in question until one half (five) of the cells in that group failed. At that time the whole group of cells was considered to have failed, and removed from test.

The bar graph in figure 7 depicts the cycle life of each cell group and its constituent cells. Each "step" in the bars indicates the failure of a cell at the corresponding test cycle as indicated on the horizontal axis.

All 20 cells of the two groups subjected to life-cycling with a shallow discharge of 25% are still operating satisfactorily after 1400 cycles in the temperature environment of +75°F and 120°F. The cycle-life test results by groups are shown in Table II.

TABLE II - CYCLE-LIFE TEST RESULTS

Cycling Range, % of Full Charge	Temperature Environment	
	75°F Group Failure (Cycles)	120°F Group Failure (Cycles)
80% to 20%	620	385
100% to 25%	252	150
100% to 50%	1168	579
100% to 75%	1400*	1400*

* No failures encountered to date.

The characteristics of the cell groups cycled in the 75°F and 120°F environments are shown on the graphs in Figures 8 through 31. The characteristic curves show the variation of the average

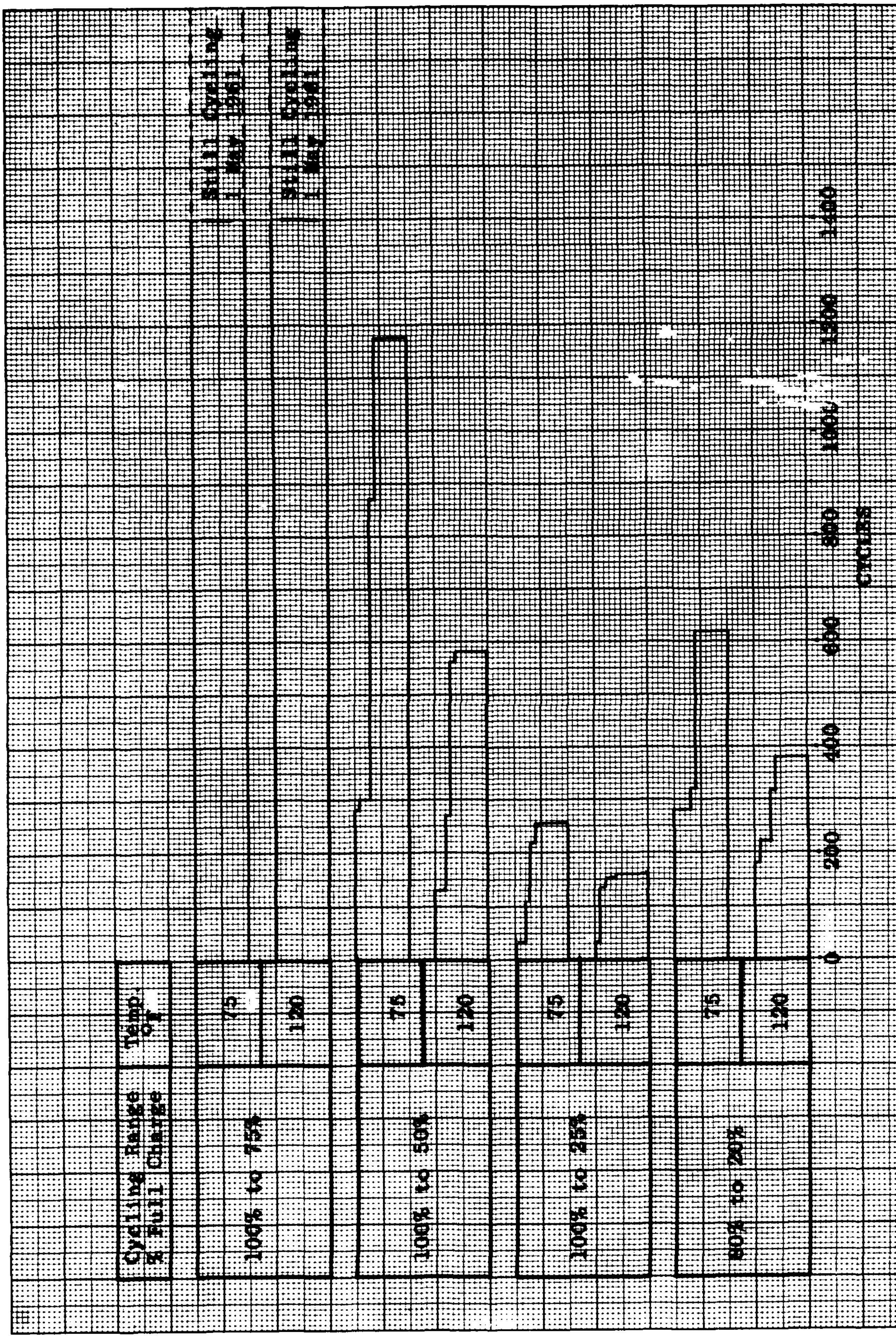

Figure 7 Bar Graph Status of Life Cycling Tests

terminal voltage of the active cells (those not removed as failed cells) for each group during the charge or discharge period for the cycles indicated. The average terminal voltage rather than the total voltage of the cell group was used as the dependent variable because the cell groups lost their common element for comparison (ten cells) when failures occurred and the cell groups had unequal numbers of cells.

Cycles were chosen for which the plots show trends of changes in characteristics by approximately equal change increments, rather than by equal cycle increments in which the data was often virtually unchanged.

1. Discharge Characteristics

In examining Figure 8 it is seen that the discharge voltage characteristic for the most shallow-discharge (25%) at 75°F, the voltage remains relatively constant throughout the discharge for each of the cycles sampled. Also, it may be noted that the general voltage level decreases slightly with increasing cycles.

In the 120°F ambient, the performance of the group cycling with a 25% discharge is shown in Figure 12. Comparing the operation of this group with that of the same discharge rate in the 75°F ambient, it is seen that the curves are less uniform and more widespread, and depart from the characteristics of the group at 75°F after approximately 300 cycles. Although the average terminal voltage remained above 1.0 volt, the wave shows a more rapid decline than the discharge characteristic at 75°F and suggests an earlier failure of the group.

Figure 9 represents the operation of the cells undergoing cycling with a 50% discharge at 75°F. Here, the effects of the deeper discharge are indicated by the more rapid decline of the voltage level (than that with 25% discharge at 75°F) particularly during the second half of discharge. For this depth of discharge, the end-of-discharge voltage for a useful discharge may be considered as 0.6 volt per cell in contrast to 1.0 volt per cell for the shallow discharges shown in figure 8. It is significant to note that the characteristics from cycle to cycle were less consistent during the cycle period, although discharge performance began at approximately the same voltage level.

The discharge performance of the cells cycled between 80% and 20% of full charge in a 75°F ambient is shown in figure 11. Here, the characteristics are quite similar to the 75% discharge in the same environment except that the terminal voltage at the beginning of each discharge was generally lower than that for the 75% discharge at approximately corresponding discharge cycles.

Figure 15 shows a sample of the operation of one group of cells cycled between 80% and 20% of full charge at 120°F. During the first portion of the cycle life the discharge characteristics had the appearance of a typical shallow discharge but this feature was short-lived as shown in the graph, after 35 cycles the voltage dropped to the 1.0 volt level at approximately two-thirds of the way through the discharge. At 190 cycles, the 1.0 volt level was reached after only 5 minutes of discharge.

2. Charging Characteristics

In examining figure 16, it is seen that the voltage characteristic of the charge position of the most shallow discharge (25%) at 75°F, the end-of-charge voltage level increases slightly with increasing cycles.

In the 120°F ambient, the charge characteristic of the group cycled in the 25% discharge range is shown in figure 20. In comparing the operation of this group with that of the same charge group in the 75°F ambient, it is seen that the end-of-charge voltages are more widespread, and depart from the characteristics of the group at 75°F after approximately 300 cycles of operation. The group at 120°F, after cycling approximately 300 cycles, reached the point of maximum charging voltage (1.55 volts) after approximately 46 minutes of the 55 minute charge period.

In figure 17 which represents the charge characteristics of the cell group in the 50% discharge range at 75°F, the effects of the deeper discharge on the charge voltages are indicated by a higher level of end-of-charge voltage, which also increases with increasing cycles.

Figure 21 depicts charge performance of the 50% discharge group at 120°F ambient. It is seen that the higher discharge rate, combined with the higher ambient temperatures, produced a wide range of end-of-charge voltages, and that the end-of-charge voltages follow no particular pattern with respect to increasing cycles of operation.

The charge performance of the cells cycled at the deep discharge rate of 75% in a 75°F ambient is shown in Figure 18. It is significant to note that the end-of-charge voltage decreased with increasing cycles.

Figure 22 shows the charge performance of the deep discharge of 75% in a 120°F ambient and also depicts a decrease in end-of-charge voltage with increasing cycles and also a decrease in the general level of charge voltage throughout the charge portion of the cycle with increasing cycles.

The charge performance of the cells cycled at the discharge range of 80 to 20% of full charge in a 75°F ambient is shown in figure 19. Here, the characteristics are quite similar to the 75% discharge in the same environment except that the charging voltages varied over a wider range during the charge portion of the cycle.

The effects of the higher ambient temperature (120°F) on the group cycles in the range of 80 to 20% of full charge are shown in figure 23. The end-of-charge voltage follows no particular pattern with respect to increasing cycles and the general level of charging voltage is higher from the start of the charge period to the end of charge.

3. Temperature Characteristics

A study was made of the variation of the cell temperatures of each cell group as it proceeded through the cycle-life test. The results are shown in figures 24 through 31. The ordinate values of each of these graphs were obtained by computing the average of the maximum temperature recorded during the corresponding cycles for each of the three cells sampled in each group. These values were plotted versus cycles, as shown in the figures. No particular pattern was noted among the different cell groups; however, the general temperature level was lower for both groups in the 25% discharge category, with respect to the groups in the other discharge ranges. The levels in the other three discharge categories were not appreciably different within either environment.

A study of the temperature variation for given cells throughout each of several cycles did not indicate a consistent pattern. It was anticipated that a definite temperature rise would occur during each discharge as a result of exothermic chemical reactions occurring during that period. It was also expected that a noticeable temperature rise would occur toward the end of the charge periods, particularly those in which a relatively high terminal voltage was present. These conditions could cause a temperature rise during that portion of an otherwise endothermic reaction period.

G. Failure Analysis

Each failed cell is examined carefully upon removal from the environmental chamber and a preliminary failure analysis report completed.

An analysis of the interior of each failed cell, including a chemical analysis, will be conducted by the battery manufacturer in accordance with a method of analysis established by the Contractor and approved by the Contracting Officer. This analysis will be made to determine the failure mechanisms and to prepare recommendations for their correction. Where deemed necessary, a complex investigation will be made to determine the more obscure failure mechanisms. The analysis will be reviewed and accepted by the Contractor prior to becoming a part of a compiled Failure Analysis Report separate from the Periodic Technical Report.

A sample Preliminary Failure Analysis Report form and a sample Procedure for Performance of Cell Failure Analysis by manufacturers are shown in Appendix I.

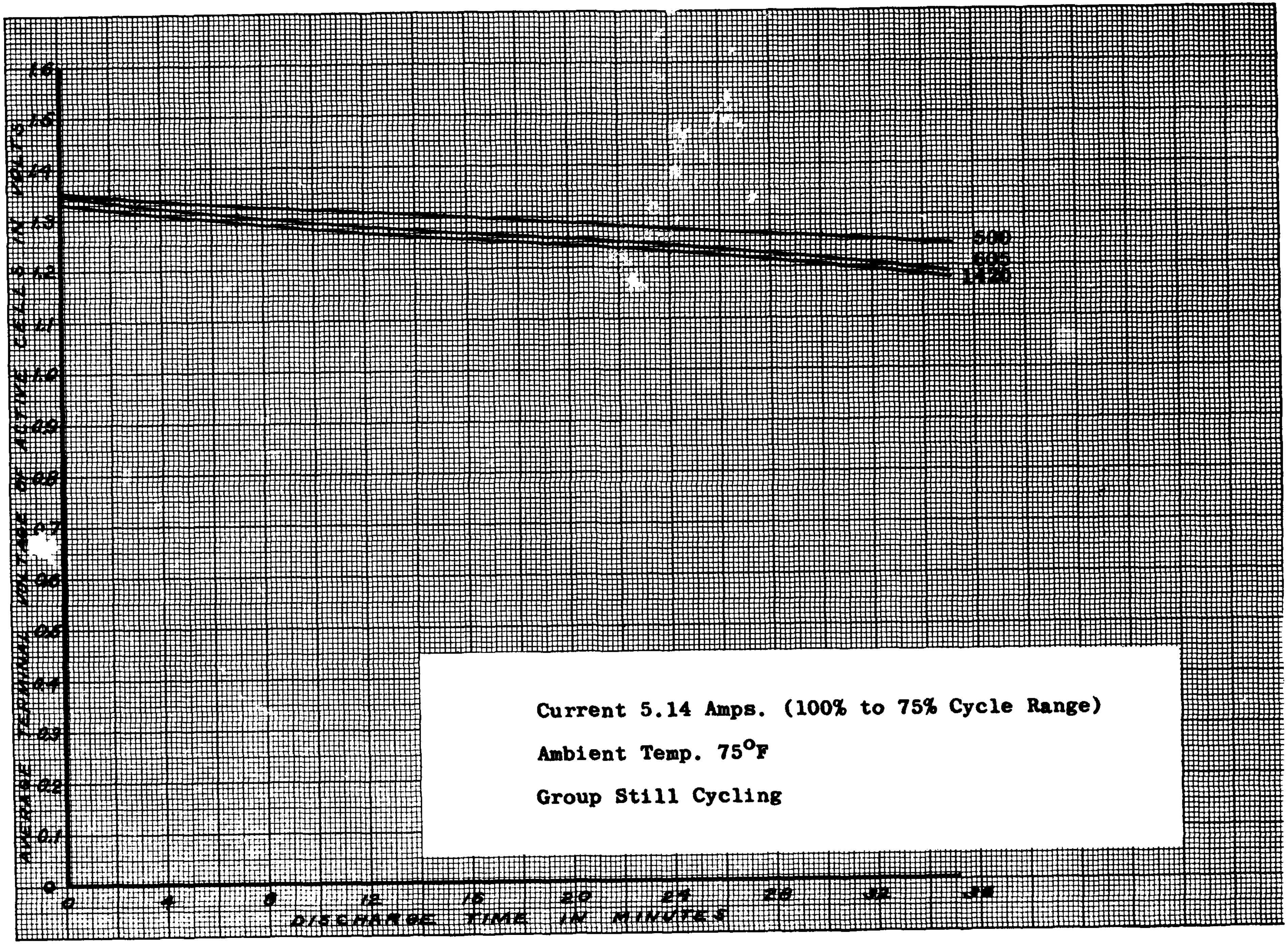

Figure 8 - Discharge Performance - Test Group I

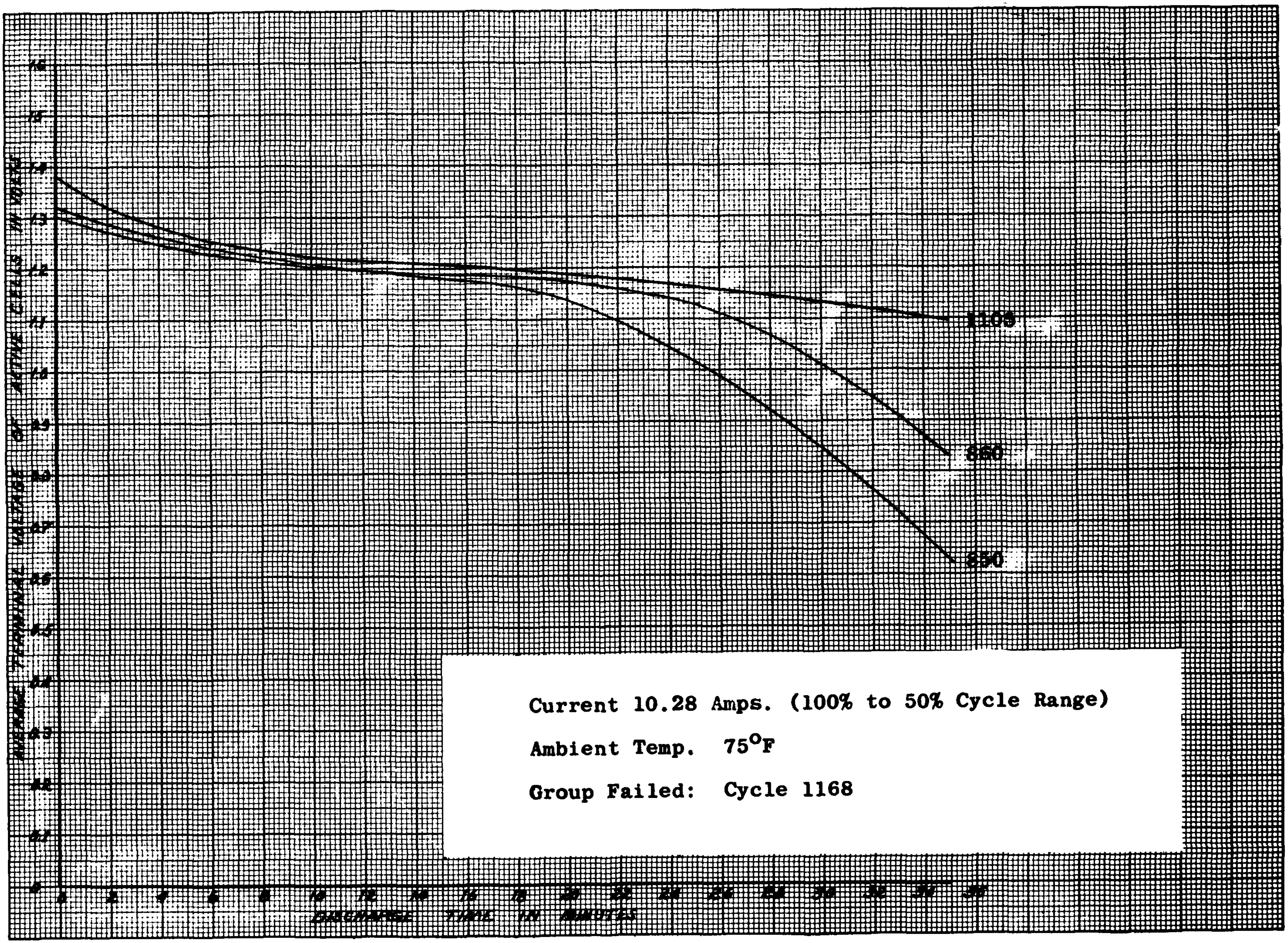

Figure 9 - Discharge Performance - Test Group II

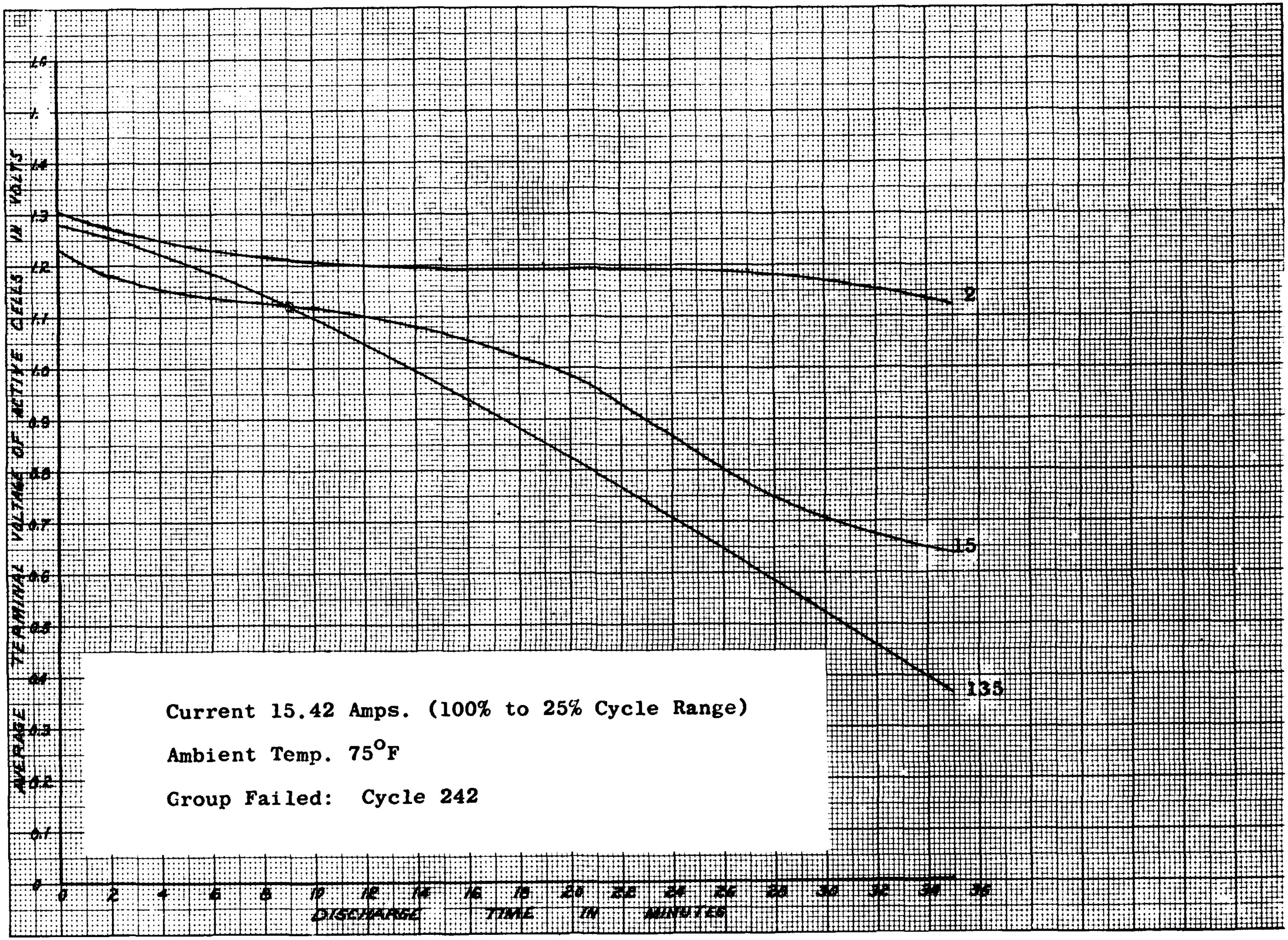

Figure 10 - Discharge Performance - Test Group III

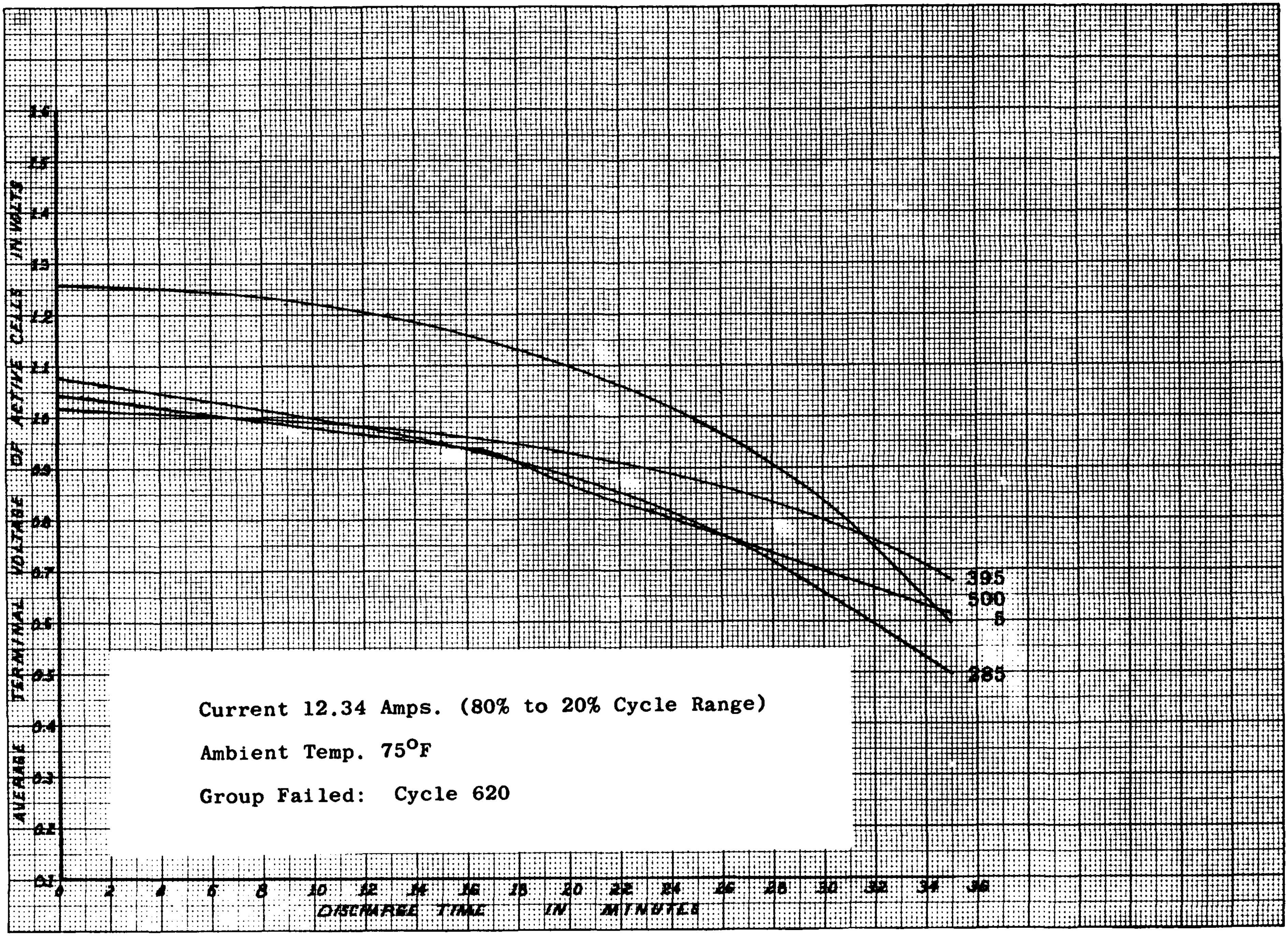

Figure 11 - Discharge Performance - Test Group IV

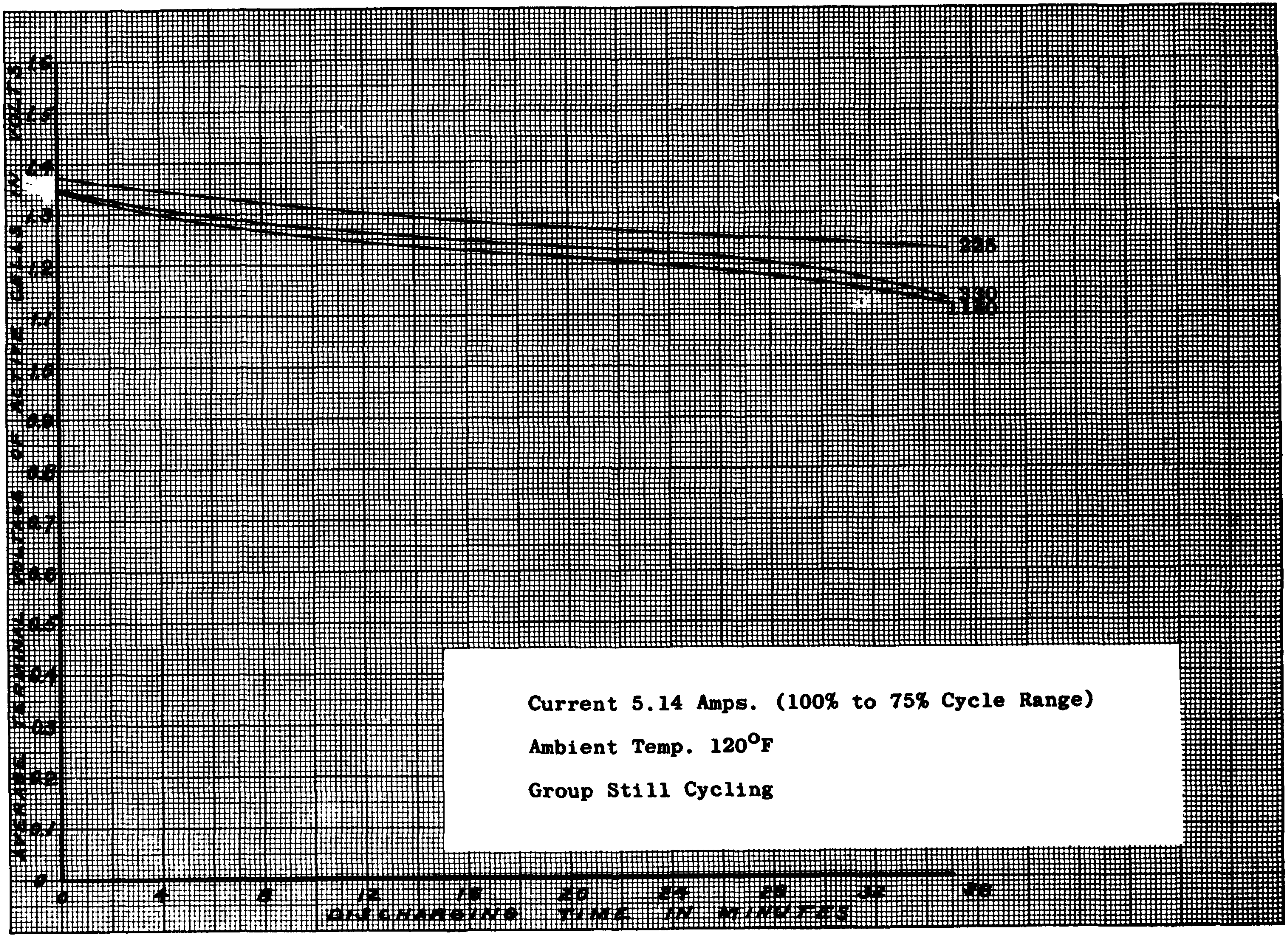

Figure 12 - Discharge Performance - Test Group V

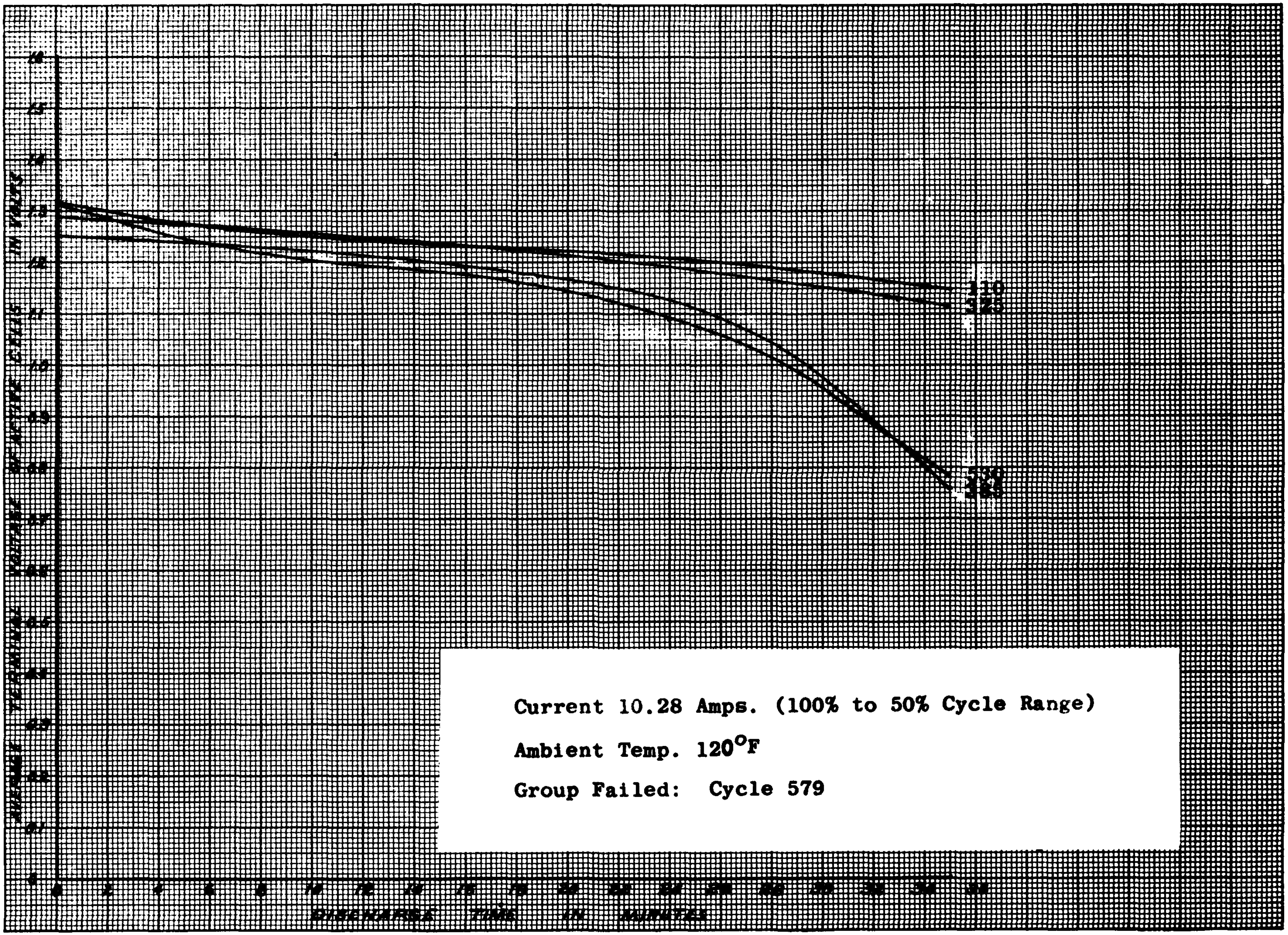

Figure 13 - Discharge Performance - Test Group VI

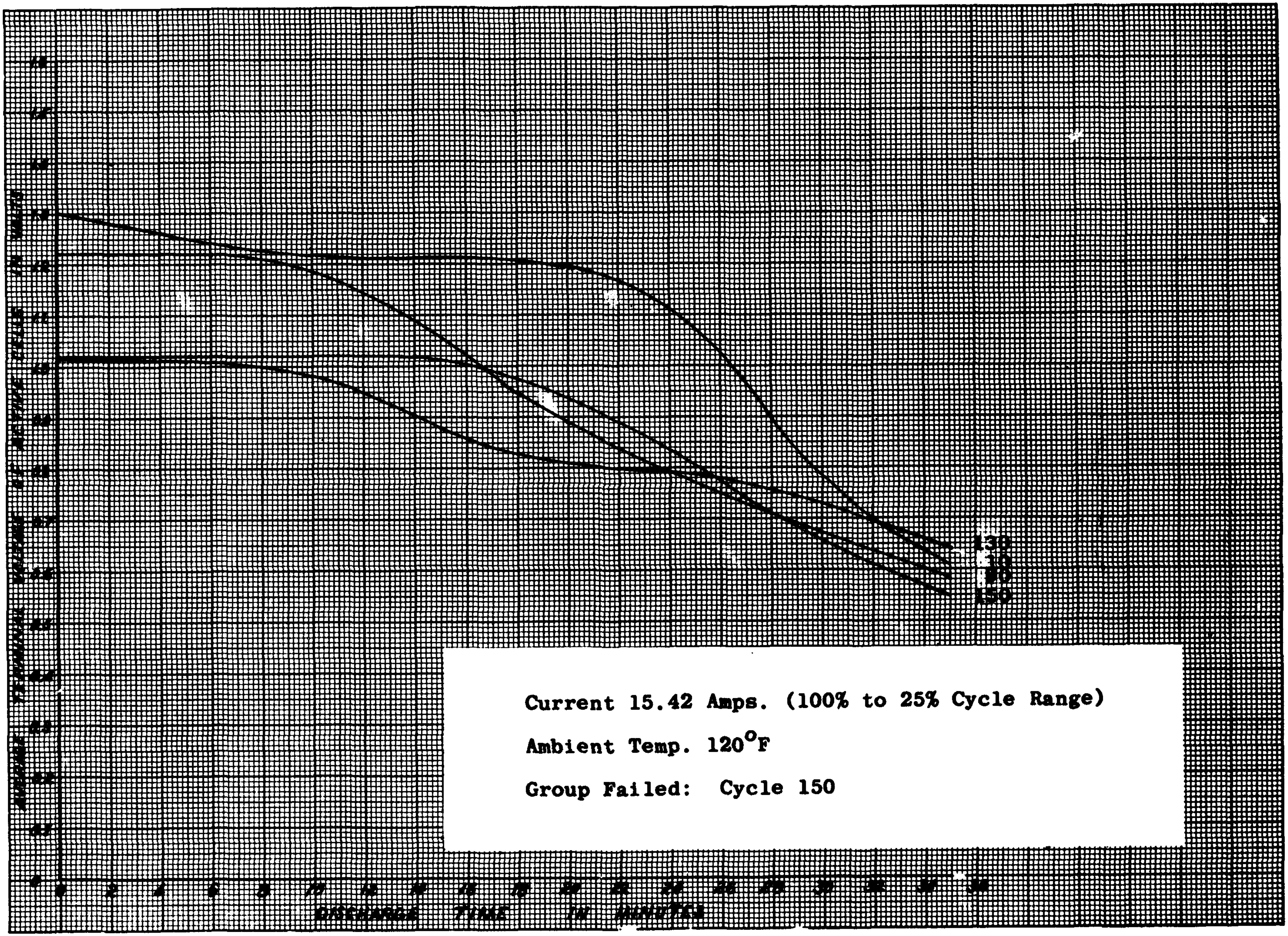

Figure 14 - Discharge Performance - Test Group VII

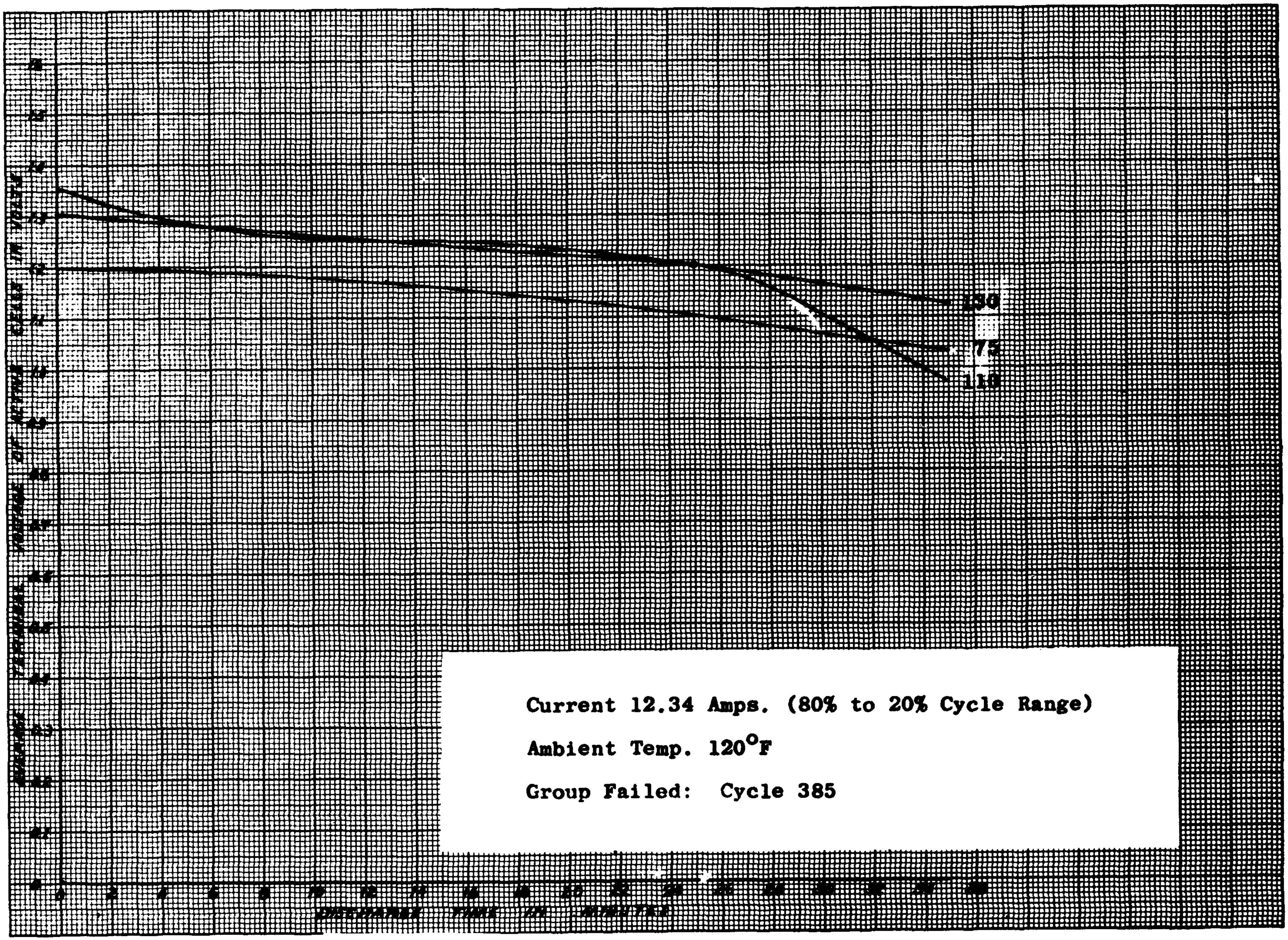

Figure 15 - Discharge Performance - Test Group VIII

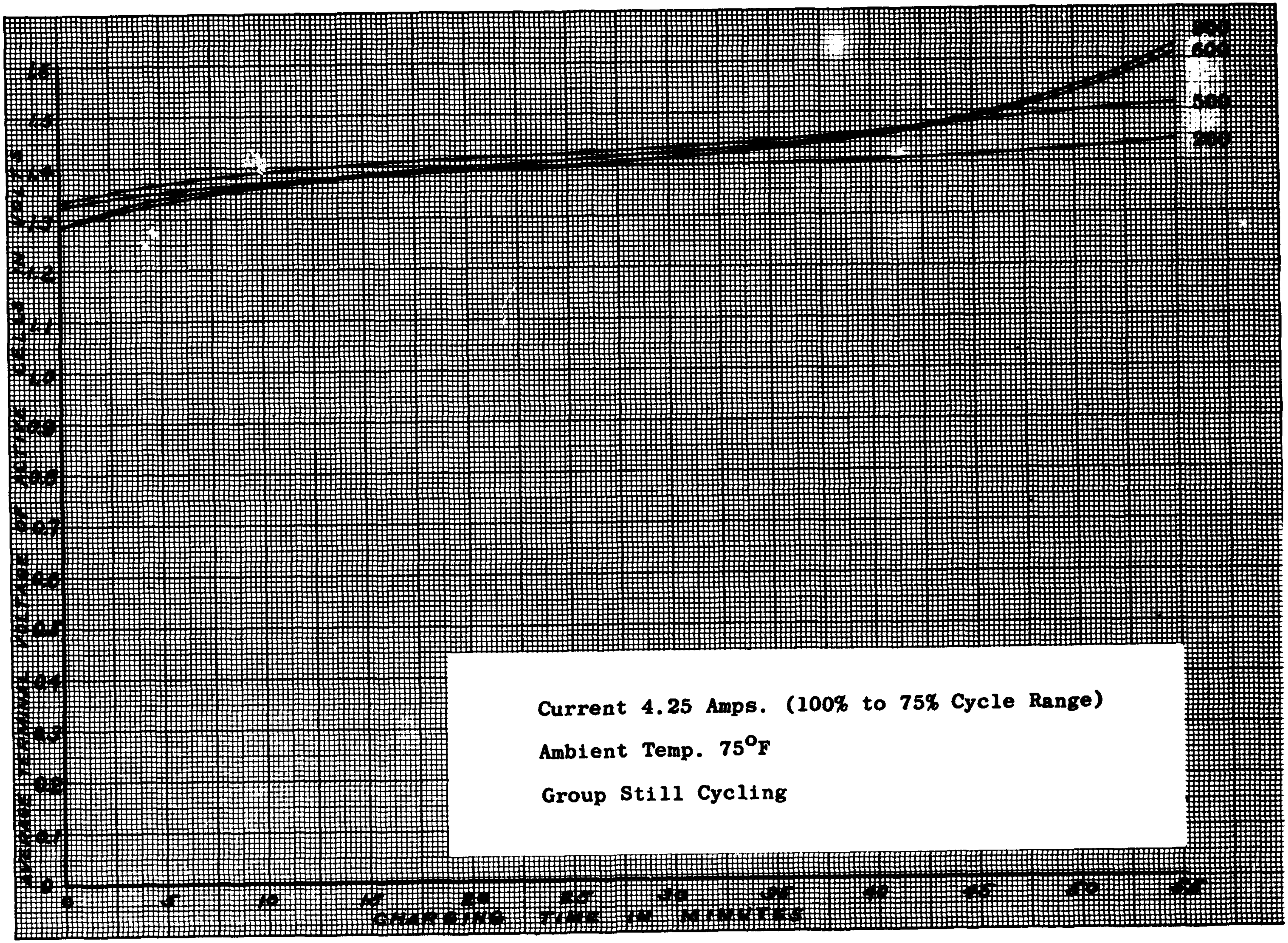

Figure 16 -Charge Performance - Test Group I

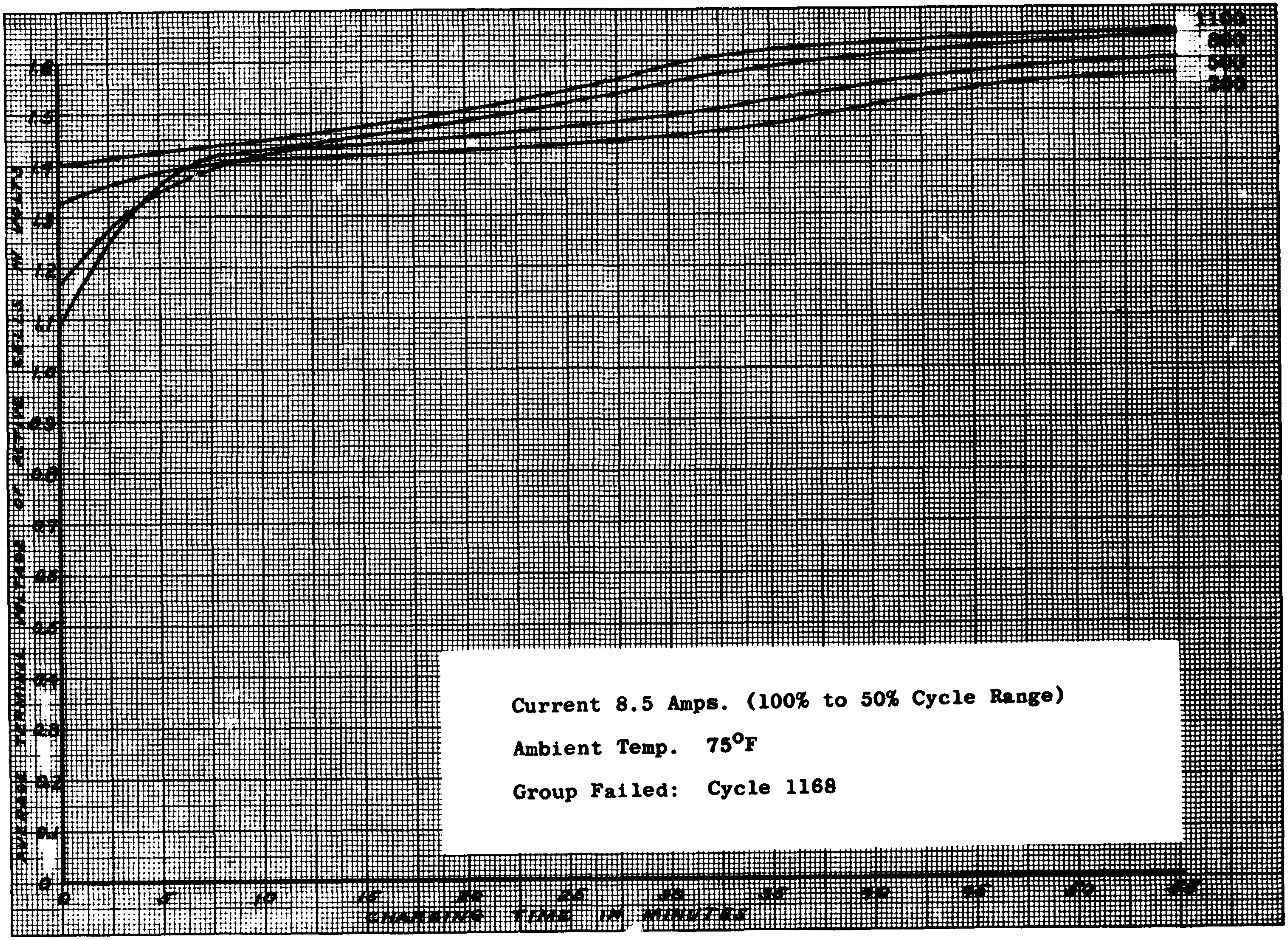

Figure 17 - Charge Performance - Test Group II.

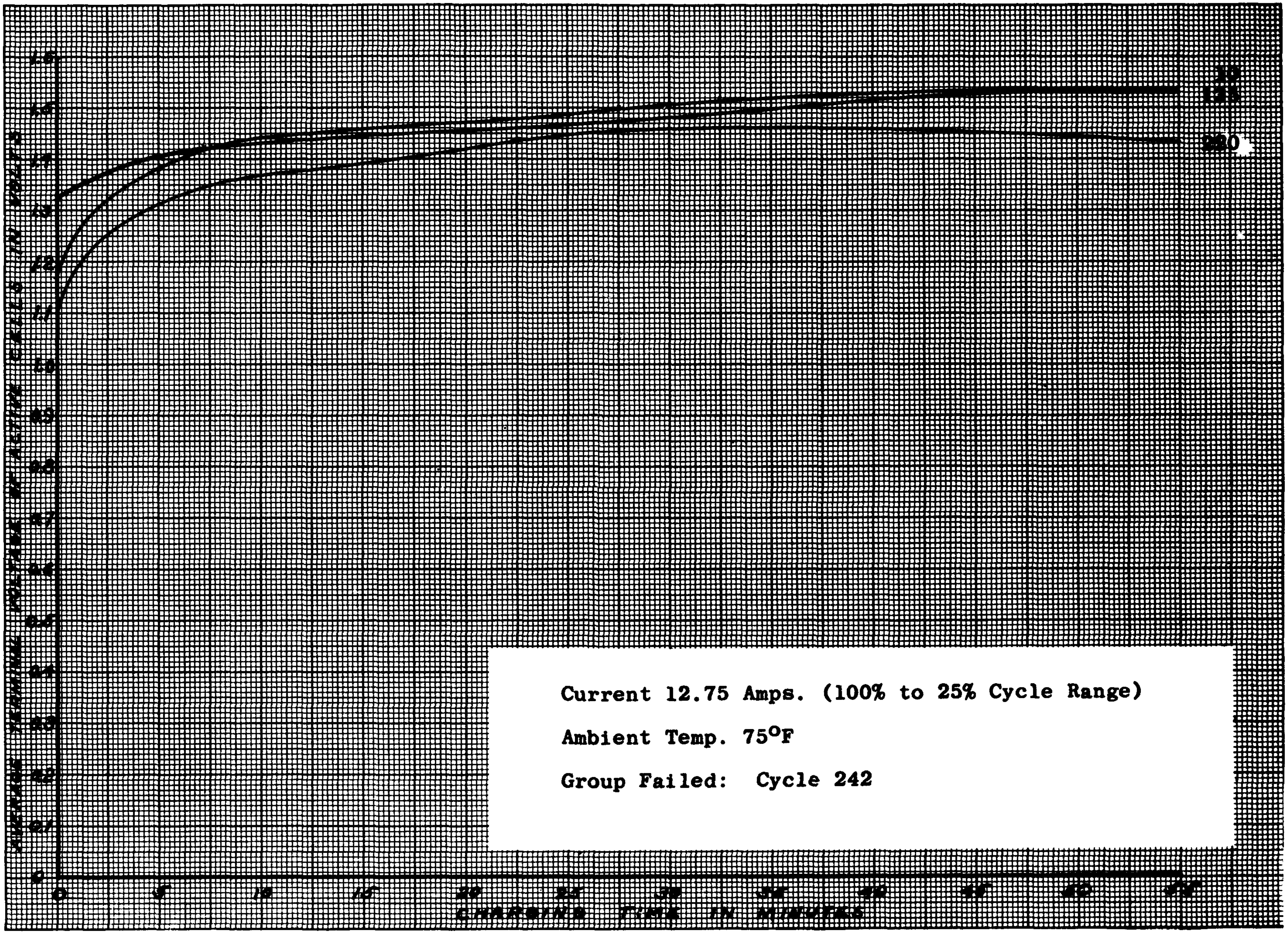

Figure 18 - Charge Performance - Test Group III

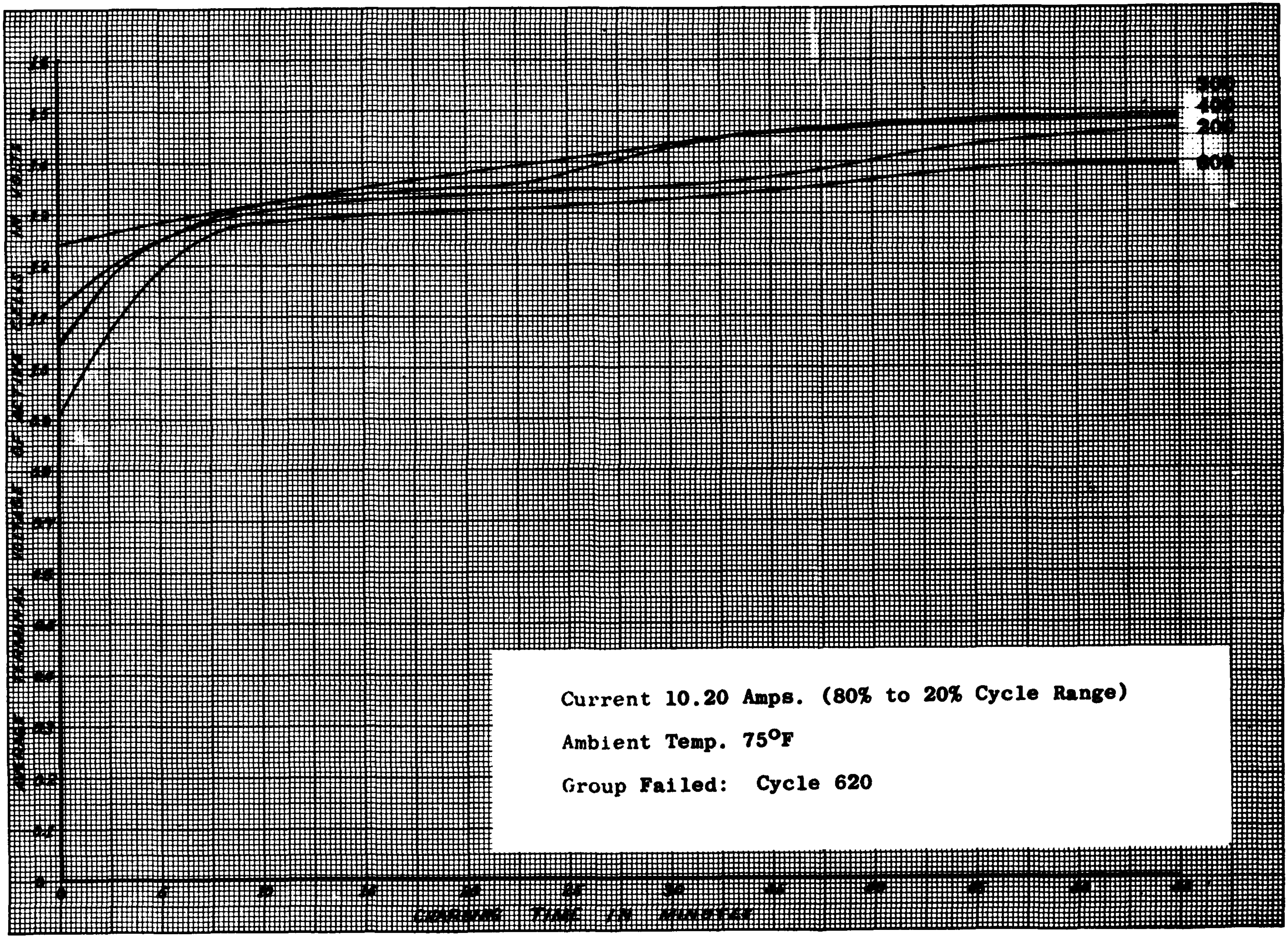

Figure 19 - Charge Performance - Test Group IV

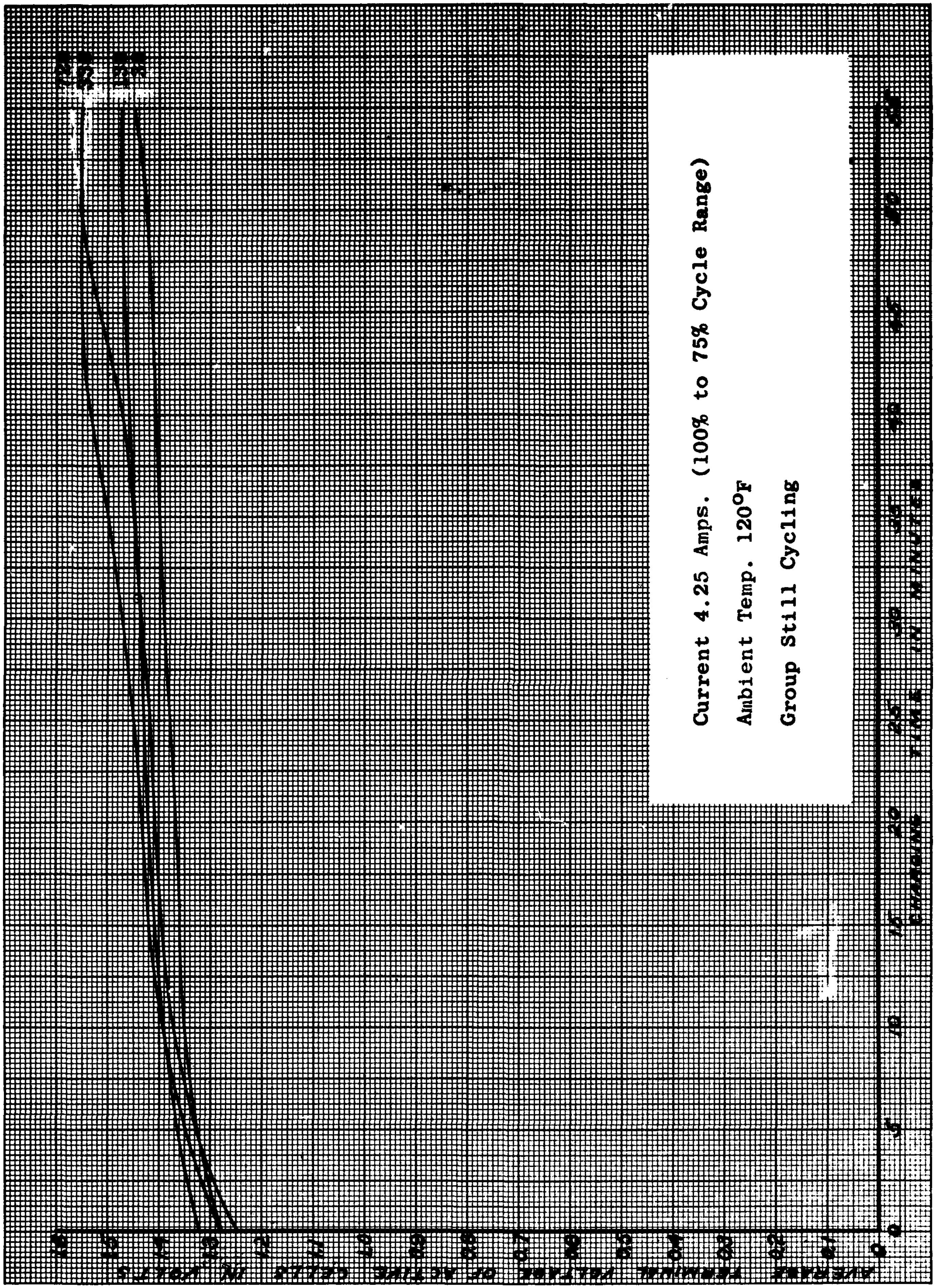

Figure 20 - Charge Performance - Test Group V

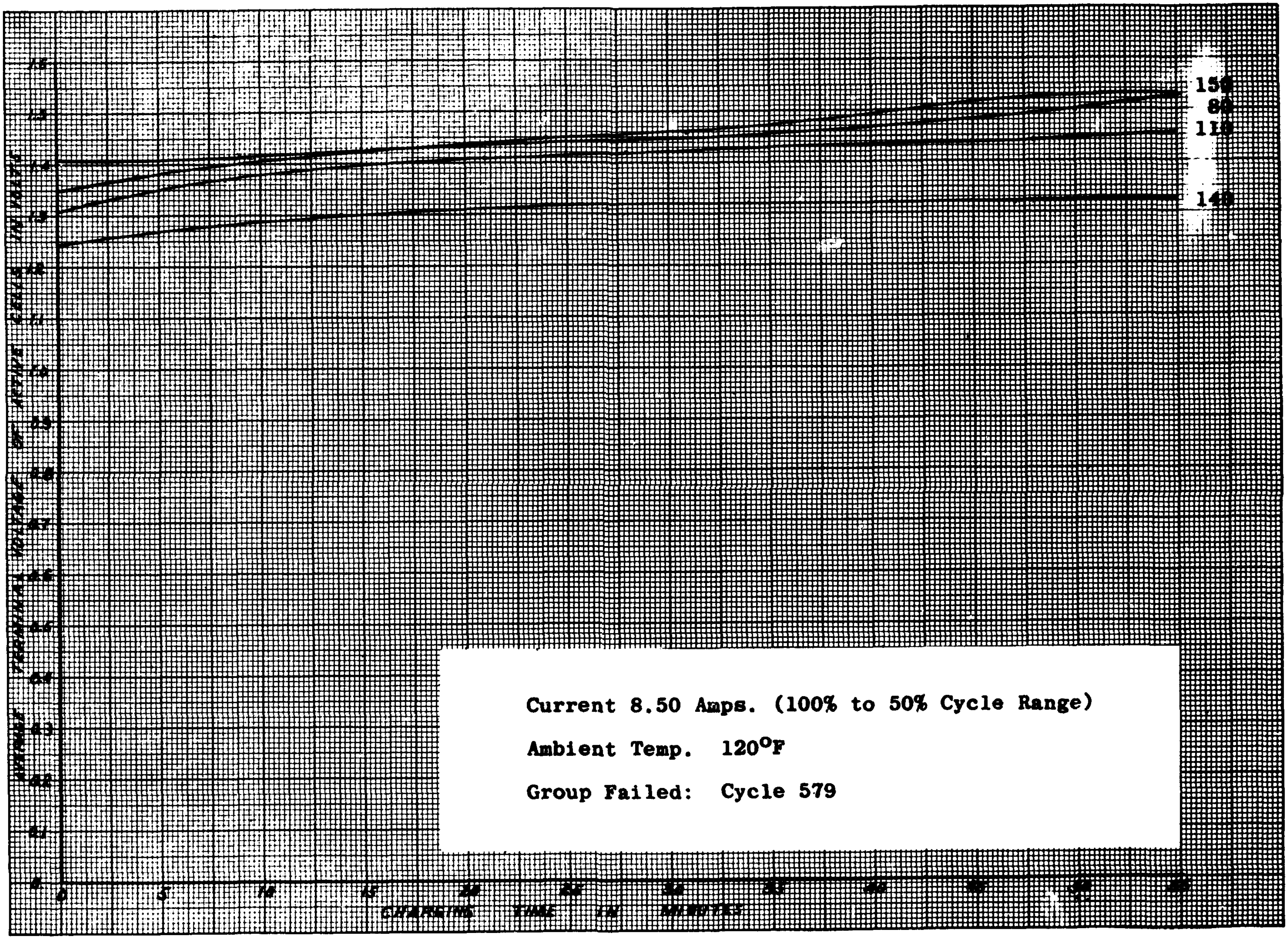

Figure 21 - Charge Performance - Test Group VI

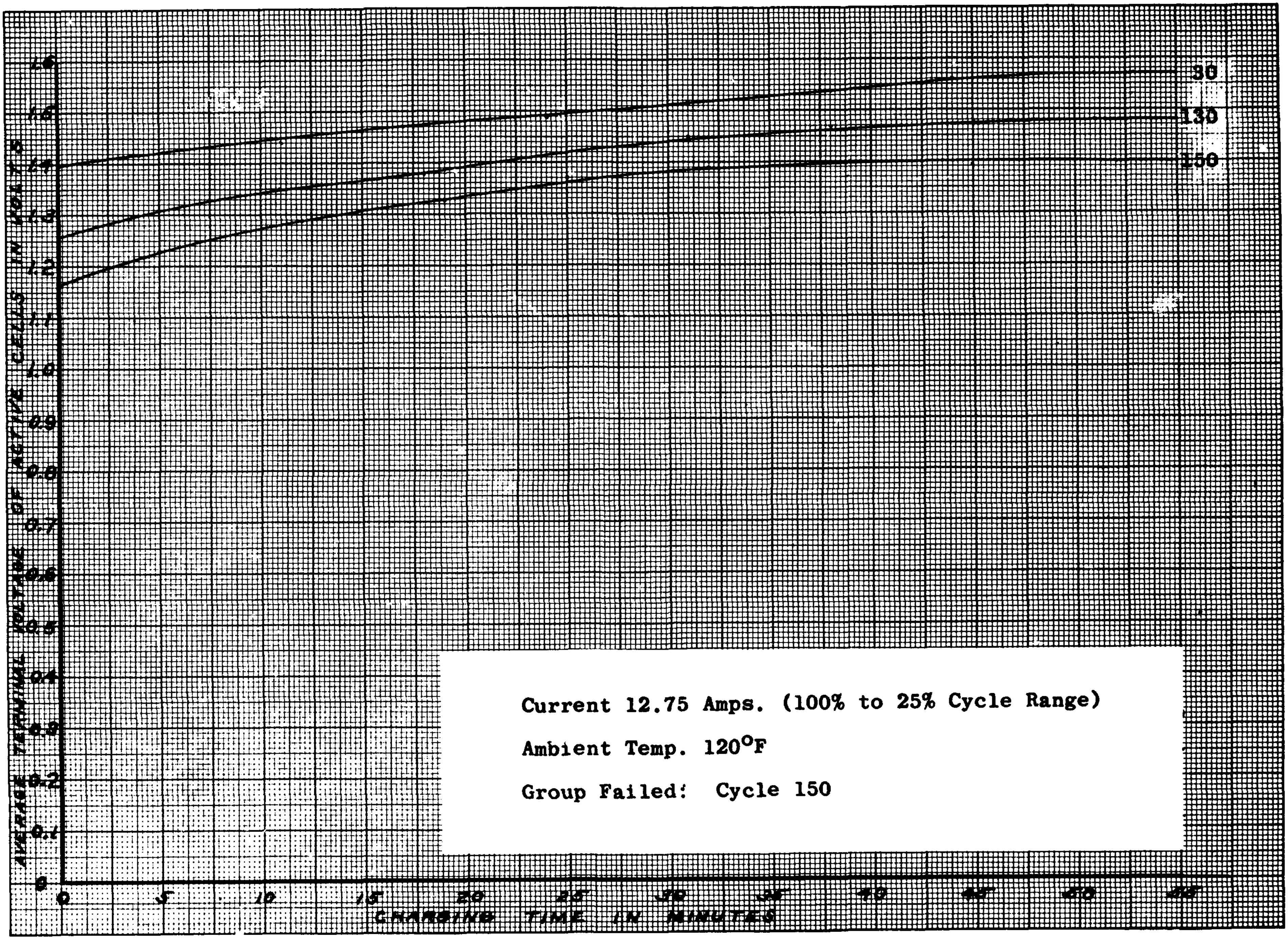

Figure 22 - Charge Performance - Test Group VII

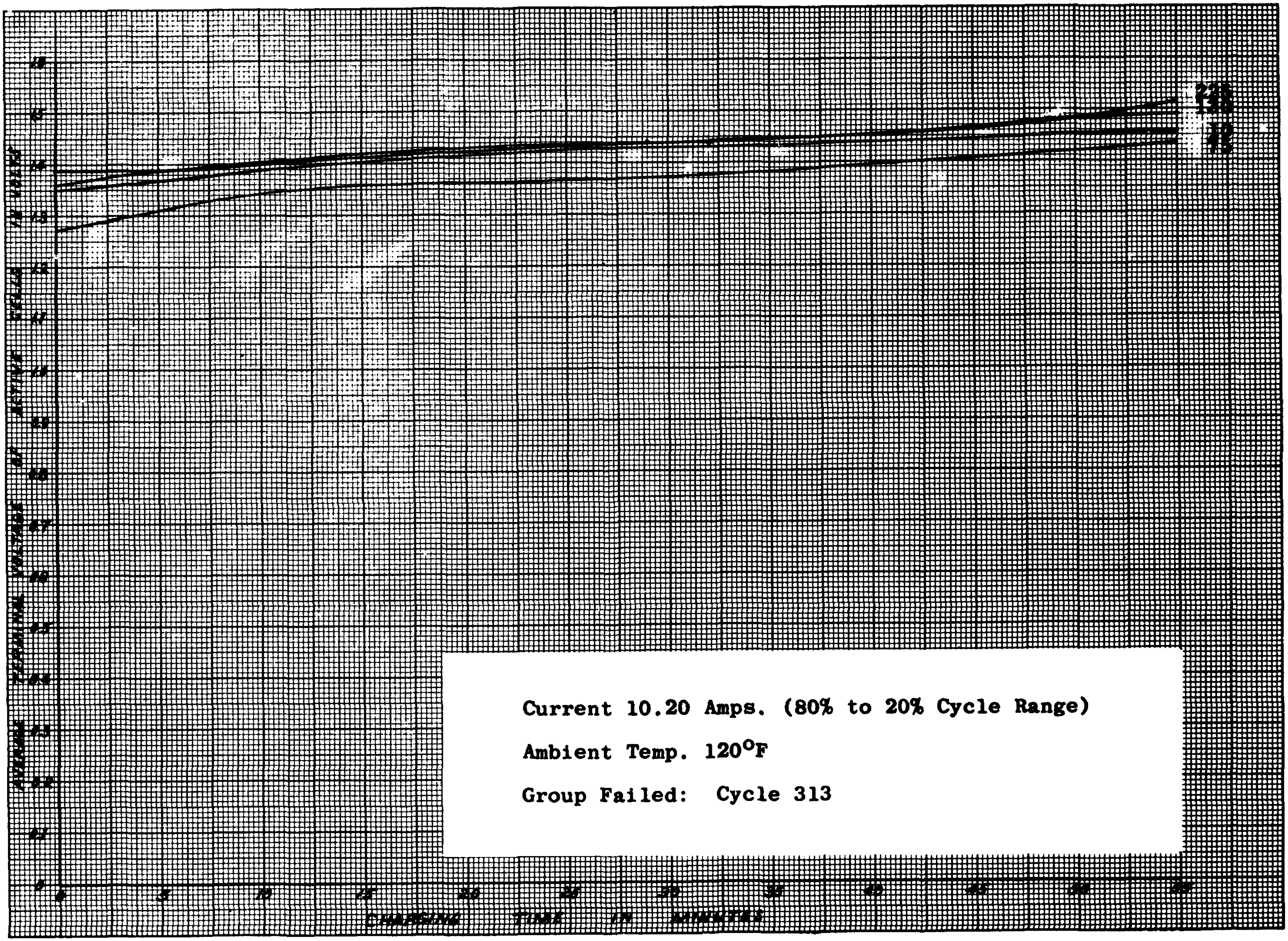

Figure 23 - Charge Performance - Test Group VIII

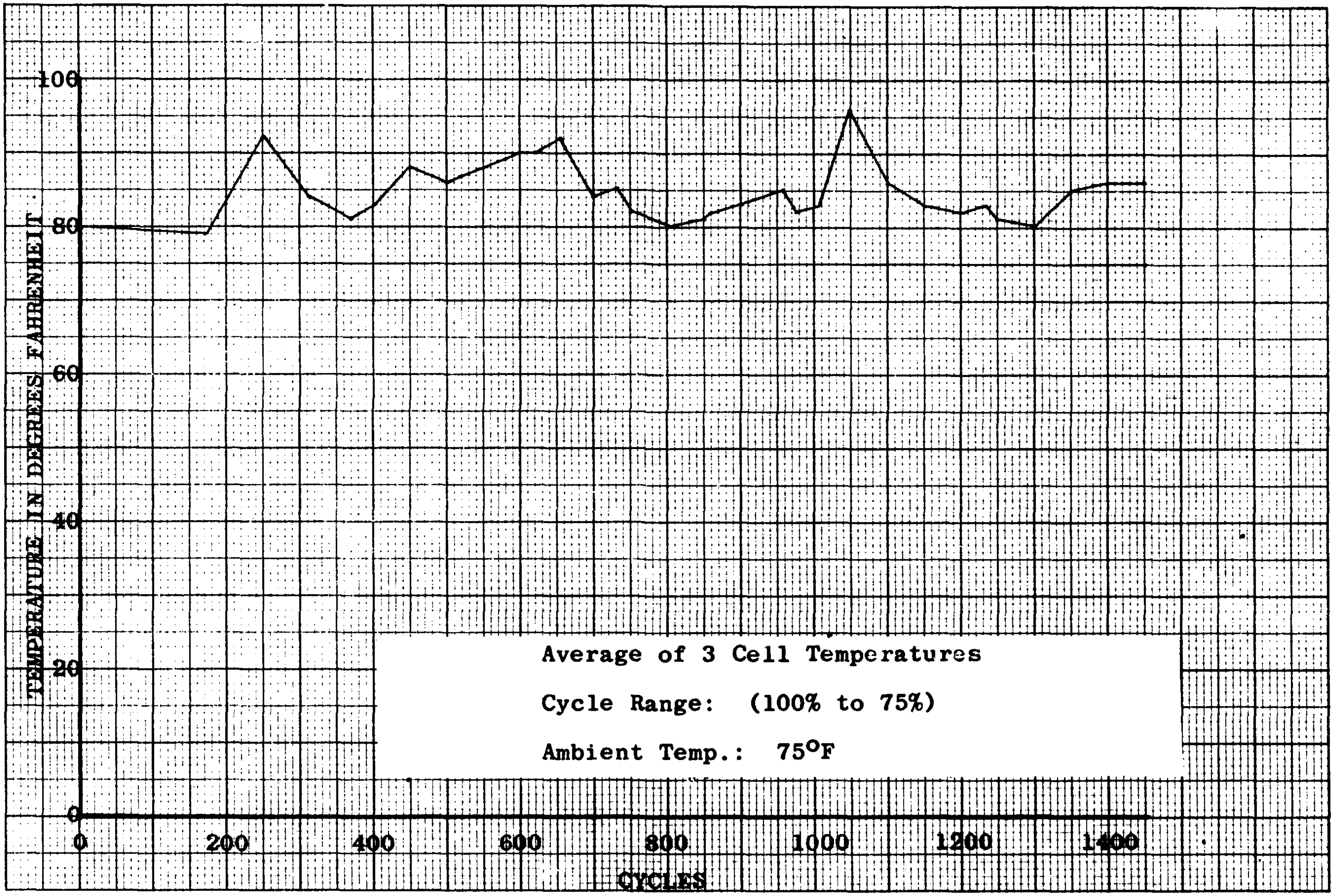

Figure 24 - Cell Temperature vs. Cycles - Test Group I

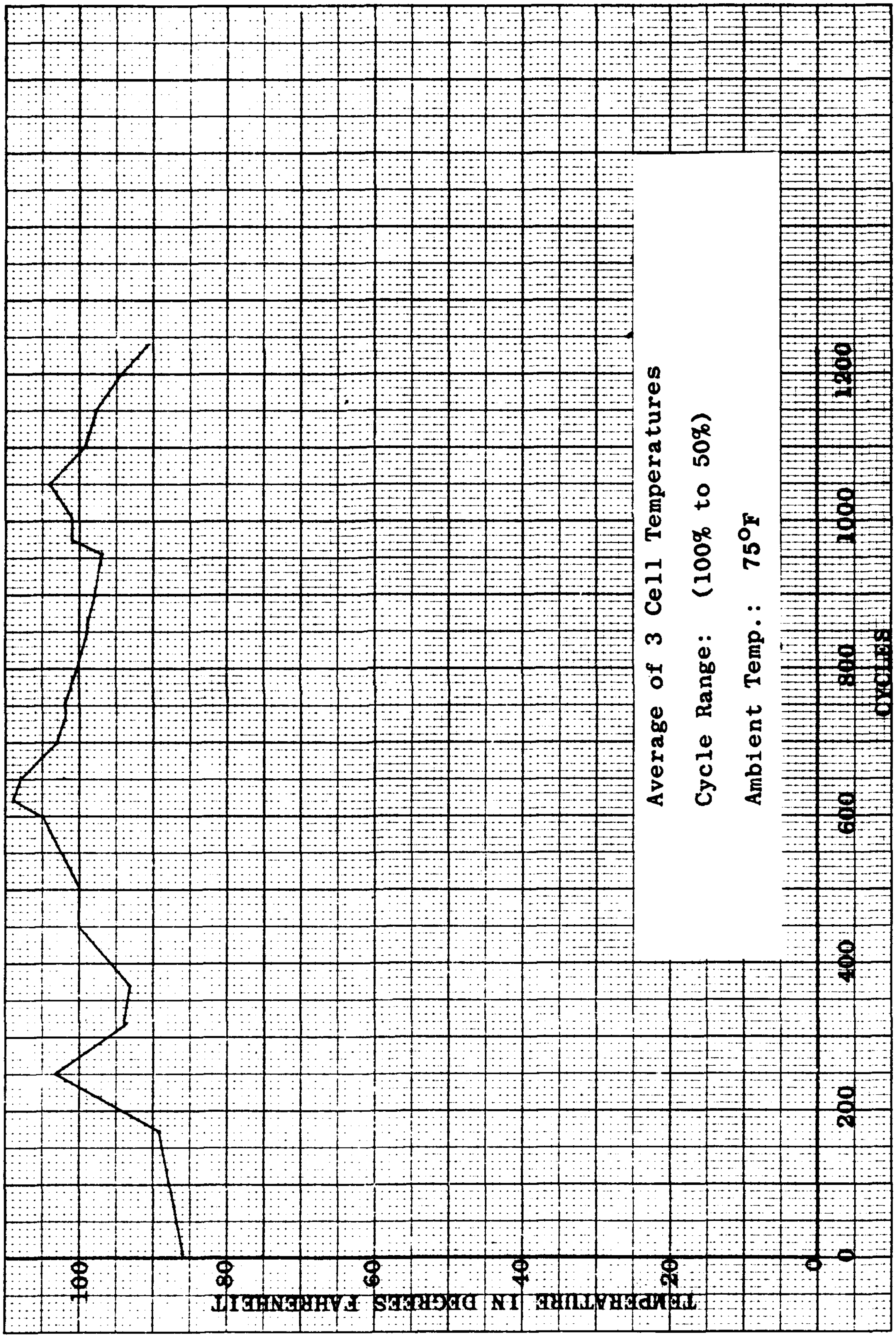

Figure 25 - Cell Temperature vs. Cycles - Test Group II

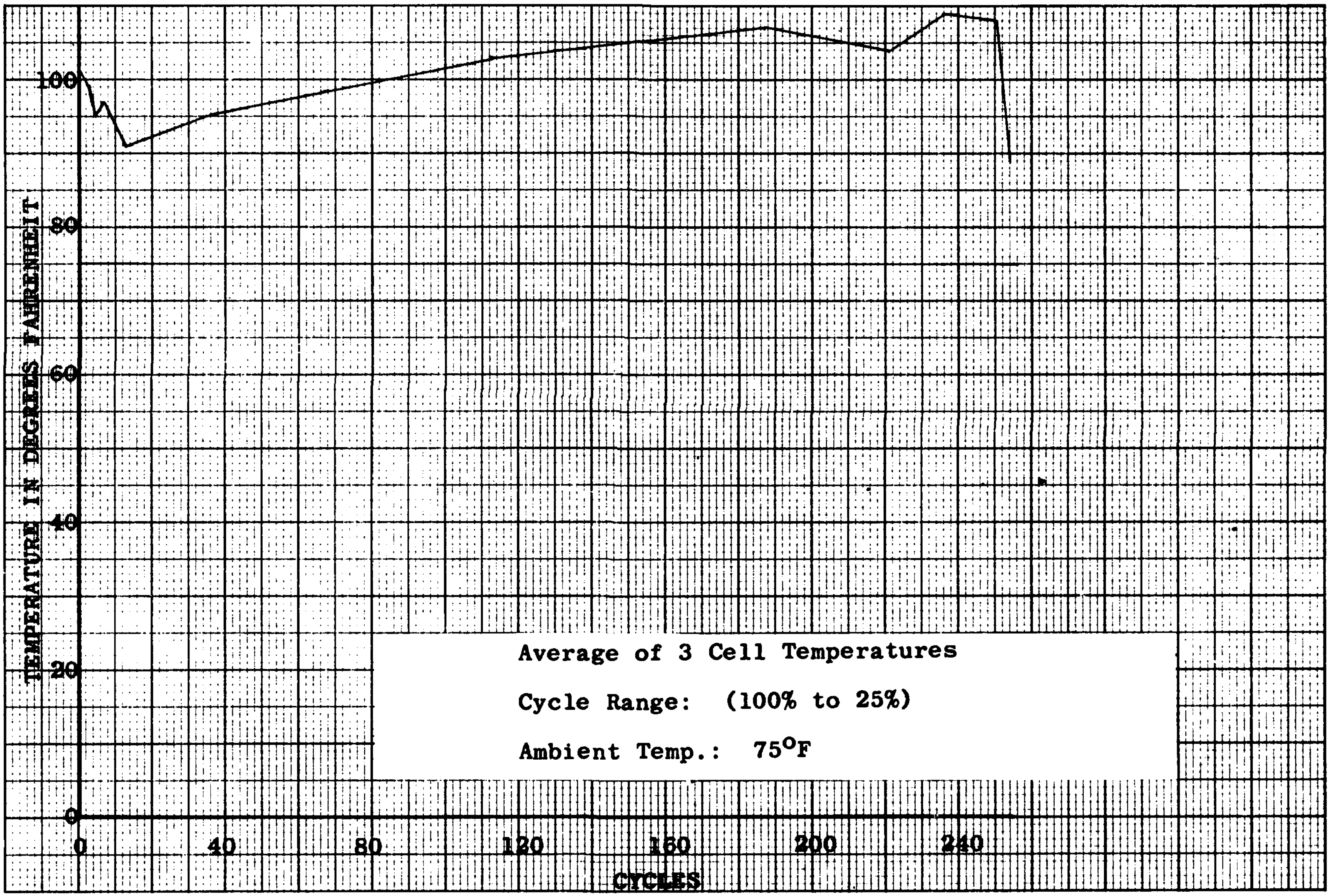

Figure 26 - Cell Temperature vs. Cycles - Test Group III

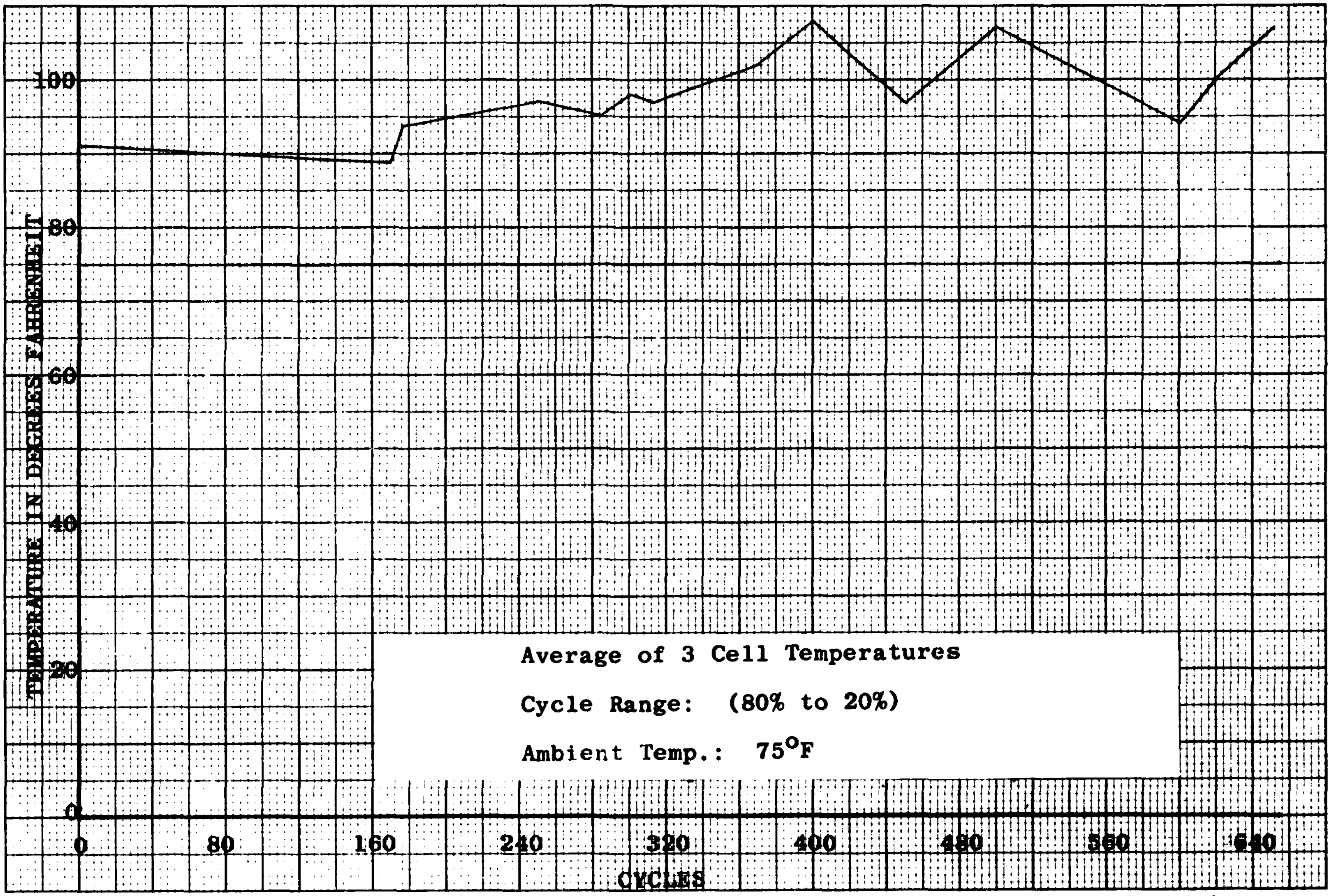

Figure 27 - Cell Temperature vs. Cycles - Test Group IV

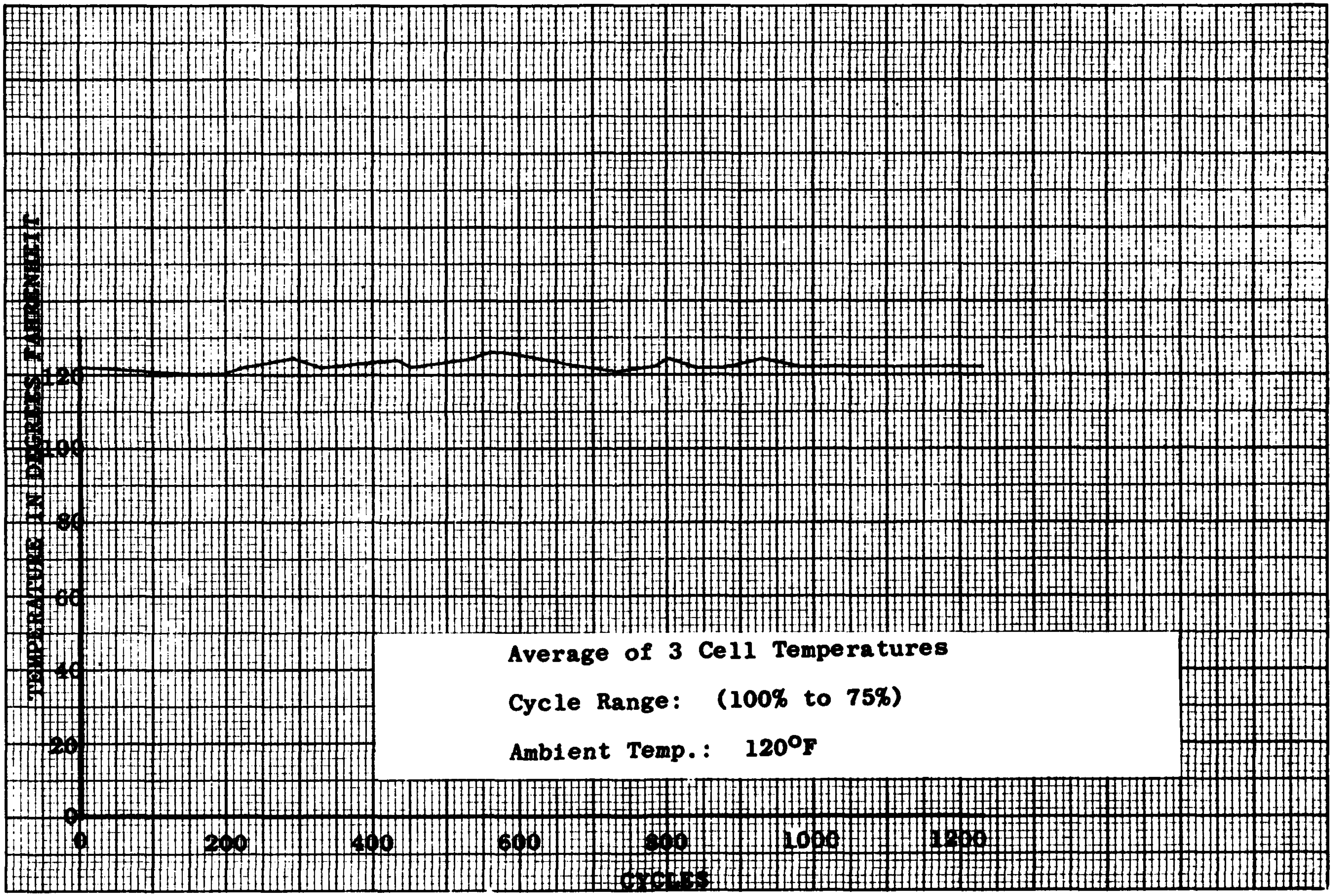

Figure 28 - Cell Temperature vs. Cycles - Test Group V

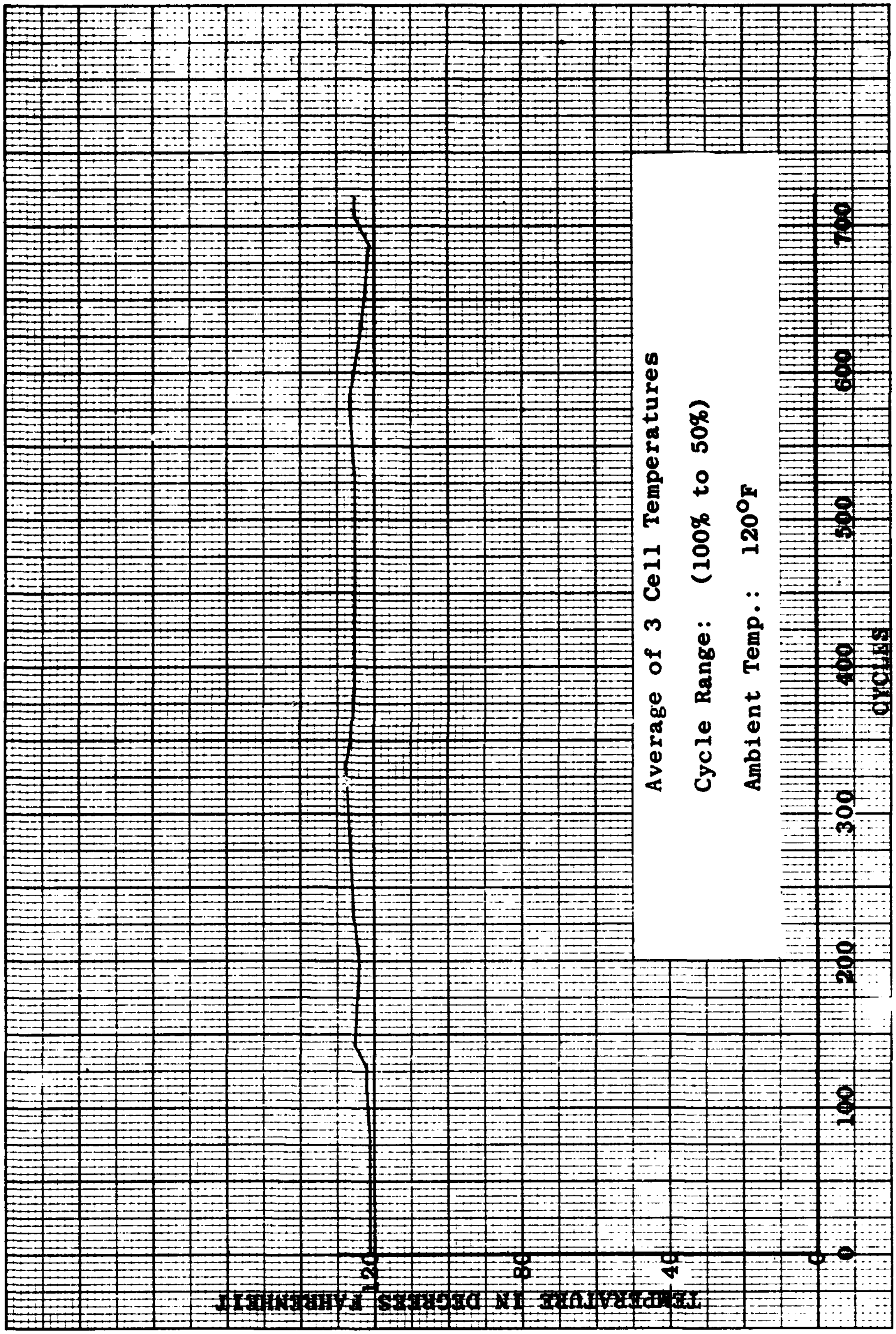

Figure 29 - Cell Temperature vs. Cycles - Test Group VI

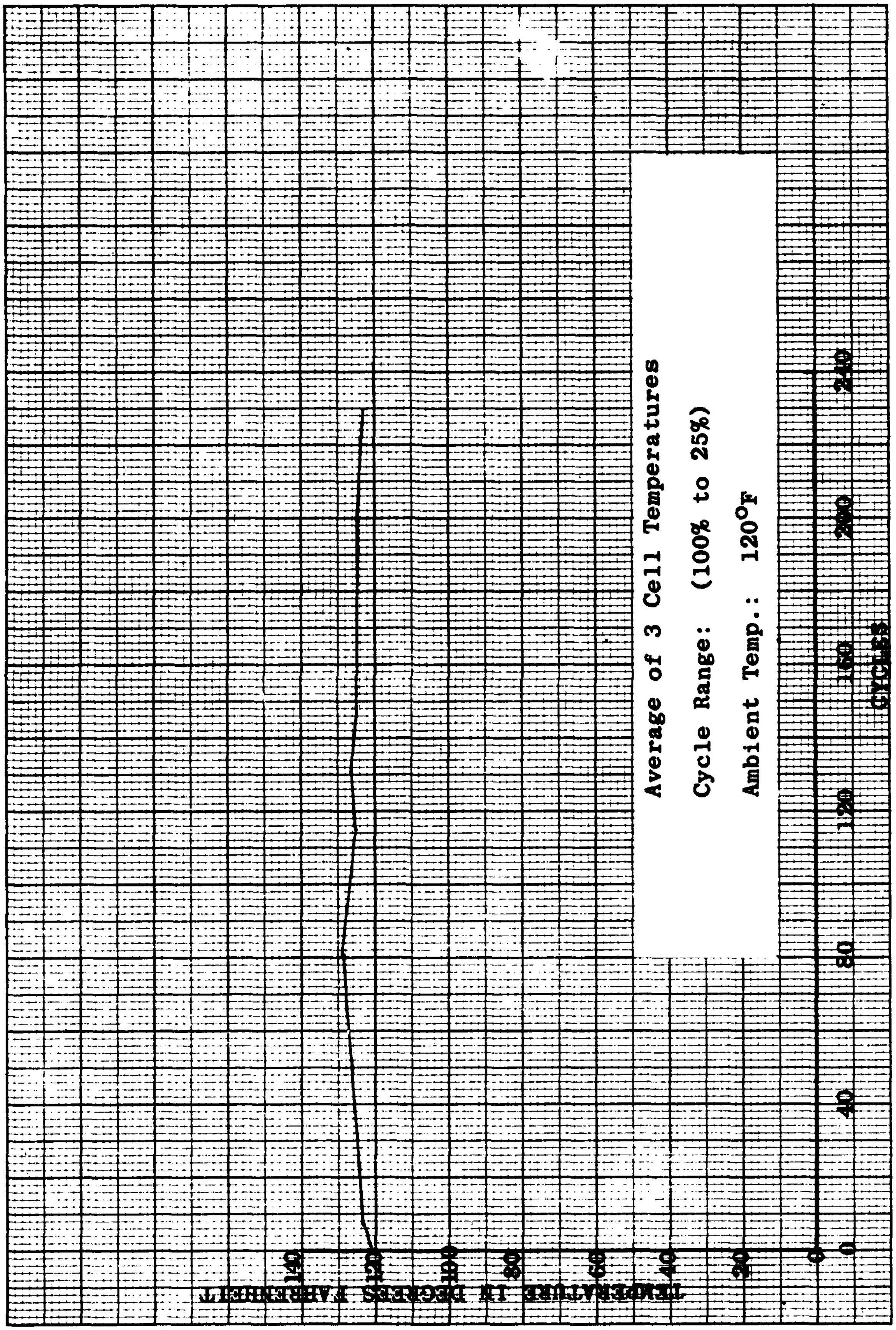

Figure 30 - Cell Temperature vs. Cycles - Test Group VII

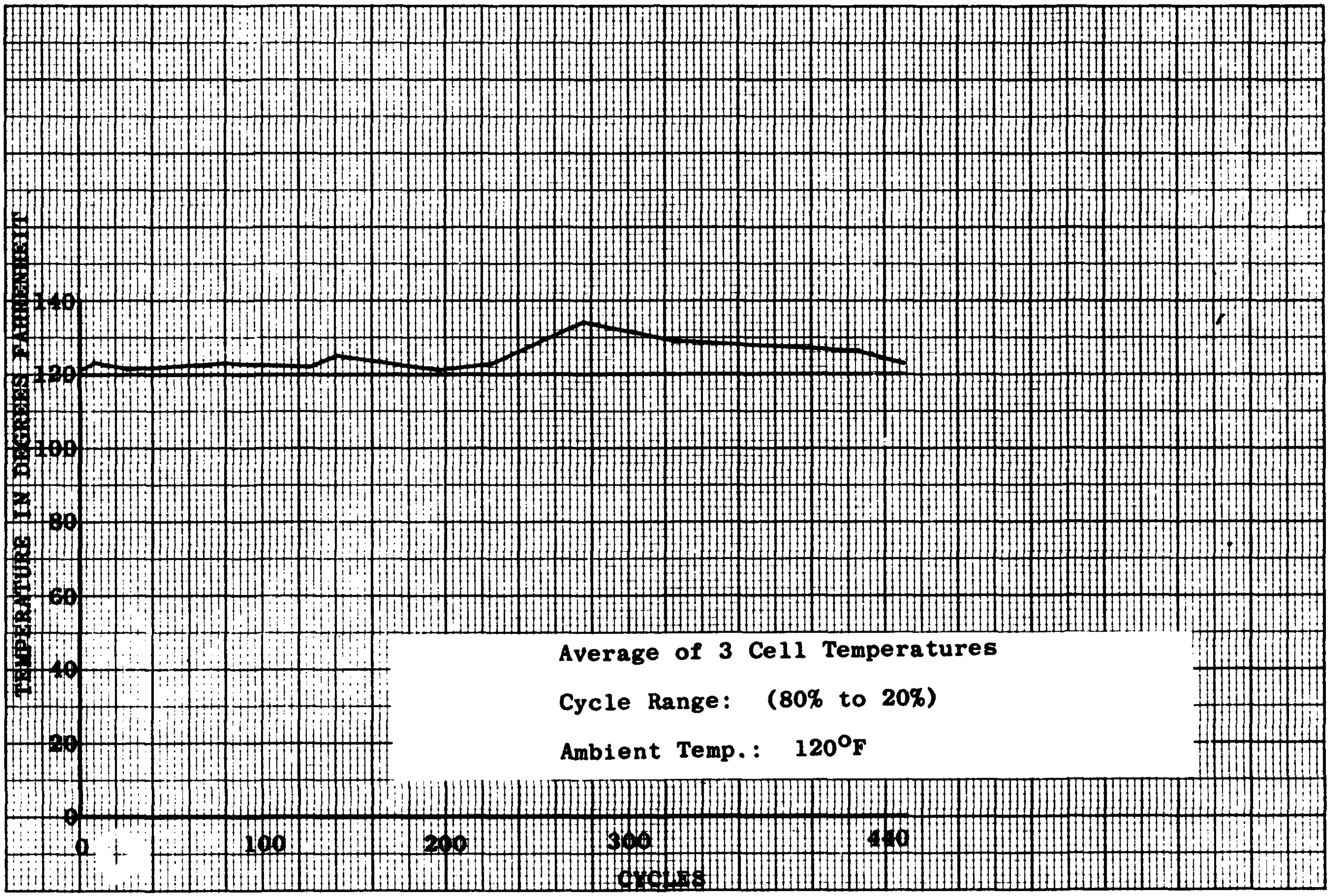

Figure 31 - Cell Temperature vs. Cycles - Test Group VIII

III. CONCLUSIONS

Based upon the data and test results obtained from the work completed in the alkaline battery evaluation program to date, some significant trends and pertinent relationships have become evident. Since only one type of sealed nickel-cadmium cells has been evaluated in the program to date, these trends and relationships would necessarily apply to those cells investigated. However, it is believed that a number of correlations presently indicated will be proved as additional types of cells, tests and life-cycles are completed and analyzed.

As shown in TABLE III - Cycle-Life Test Results, the life of the cells in each temperature environment was consistently shorter as the depth of discharge steps were increased. Also, the cycle-life at each depth-of-discharge was considerably less in the temperature environment of 120°F than 75°F.

These results show that depth-of-discharge and ambient temperatures are important factors in governing cycle-life of the nickel-cadmium batteries and indicate that the cycle-life is considerably decreased as depth-of-discharge or ambient temperature above room temperature is increased.

It is believed that the shorter cycle-life at an ambient temperature of 120°F as compared to the results at 75°F, is largely a result of a higher rate of degradation of the cellulose separator material at the higher temperature. Such deterioration of the separator may result in less coherent fibers, which promotes shorts between plates by punctures, separations and general disintegration.

The tests indicate that the internal resistance of the cells greatly increases at temperatures below zero degrees F. This characteristic necessitates an increased charging voltage to obtain any reasonably large depth-of-discharge cycling at constant current in short orbit times (90-100 minutes) at temperatures below zero degrees F.

The internal resistance varies considerably from cell to cell within a test group during cycling tests for a given set of test conditions, which suggests non-uniformity in cell behavior or construction.

Based upon the graphic results of the charge-discharge characteristics and the results of the cycle-life and low-temperature tests, the optimum performance of the cells in terms of voltage stability, capacity repeatability and cycle-life hours, occurs when the cells are operated or used with shallow discharges at ambients near room temperature. The marked differences in the test results among depth-of-discharges and temperature environments, indicates that the limiting operating parameters for satisfactory cell performance will be more clearly defined as additional cells are tested and cell failure analyses are obtained.

IV. FUTURE WORK

A. Evaluation of Additional Alkaline Cells and Batteries

In the near future, it is anticipated that the following units will be procured by bid:

180 Sealed Nickel-Cadmium Batteries
220 Silver-Cadmium Cells
Six (6) 28-Volt Silver-Cadmium Batteries
220 Silver-Zinc Cells
Six (6) 28-Volt Silver-Zinc Batteries

The specific cells to be procured or the ampere-hour capacities have not yet been determined.

Prior to acceptance of cells and batteries for cycle-life tests, data and information will be obtained to assure that cells procured for evaluation are capable of meeting the following mechanical test requirements:

Vibration -- in accordance with Procedure XIV of MIL-E-5272C (ASG) except that 10 g will be used in lieu of 20 g.

Acceleration -- in accordance with Procedure III of MIL-E-5272C (ASG) except that 18 g will be used in lieu of 14 g.

Shock -- in accordance with paragraph 4. 15. 5. 1 of Specification MIL-E-5272C (ASG) except that 40 g will be used in lieu of 15 g.

Operation in any position.

Operation in a pressure of 10^{-9}mm of Hg.

1. Nickel-Cadmium Cells and Batteries

It is anticipated that cycle analysis will be conducted on 180 individual sealed cells and six (6) 20-cell batteries, with a charge-discharge cycle period representing that of a 90-minute space-vehicle orbit. This period will consist of 55 minutes of charge and 35 minutes of discharge. Life-cycling will be conducted on 150 cells, leaving 30 cells for preliminary tests in which the maximum allowable constant-current charging rate will be determined for each of the five temperature environments to be used in life tests. The temperatures that will

be used are -30°F, 0°F, +75°F, +120°F and +140°F. The six 20-cell batteries will be cycled at 75°F.

The 150 individual cells to be life cycled will be divided into 15 groups of ten (10) cells connected in series. Three (3) groups of cells will be placed in each of the five temperature environments. One of these groups will be cycled between 100% of full charge and 75% of full charge, hereafter referred to as a 25% discharge, the second group between 100% and 50% of full charge (50% discharge), and the third between 100% and 25% of full charge (75% discharge).

The six (6) 20-cell batteries will be life cycled with two (2) batteries being cycled between each of the two (2) states of charge as described for the individual cells.

A summary of the cycle-life tests on the additional nickel-cadmium cells and batteries is shown in chart form in Tables III, IV, and V.

2. Silver-Cadmium and Silver-Zinc Cells and Batteries

Cycle analysis will be conducted on 220 individual cells and six (6) 28-volt batteries of each type. Life cycling will be conducted on 192 cells of each type, leaving 28 cells of each type for preliminary tests in which the maximum allowable charging rate will be determined for each of the four (4) temperature environments to be used in life tests. The temperatures that will be used are 0°F, +40°F, +75°F, and +120°F. The six (6) 28-volt batteries of each type will be life cycled at +75°F.

The 192 cells of each type to be life cycled will be divided into two (2) equal sections of 96 cells of each type. One section will be cycled with a charge-discharge cycle period representing that of a 2-hour space-vehicle orbit. This period will consist of 85 minutes of charge and 35 minutes of discharge. The second section will be cycled with a charge-discharge cycle period representing that of a 24-hour space-vehicle orbit. This period will consist of 22 hours and 48 minutes of charge, and one (1) hour and 12 minutes of discharge.

The 96 individual cells of each type to be life cycled in each simulated orbit will be divided into 12 groups of eight (8) cells connected in series. Of these, three (3) groups of cells will be

placed in each of four (4) temperature environments. One of these groups will be cycled between 100% and 75% of full charge, and the second between 100% and 50% of full charge, and the third between 100% and 25% of full charge.

The six (6) 28-volt batteries of each type will all be cycled at +75°F with three (3) batteries of each type in each of the two (2) simulated orbits. In each orbit cycle, one (1) battery of each type will be cycled between each of the states of charge as described for the individual cells.

A summary of the cycle-life test conditions for silver-cadmium and silver-zinc cells and batteries is shown in chart form in Tables III, IV and V.

B. Recommended Research Program

A research program will be recommended for the correction or elimination of any definite failure mechanisms established as a result of an investigation of a sufficient number of failures occurring on those cells procured for the basic program.

C. Study of Techniques and Methods of Charging the Nickel-Cadmium Battery When Using Solar Voltaic Electrical Systems

A wiring diagram and a detailed description of a system employing optimum techniques and methods will be included as a separate appendix of a periodic technical report following a study of solar voltaic electrical systems.

TABLE III

NICKEL - CADMIUM				
Orbit Period: 90 Minutes Charge: 55 Minutes Discharge: 35 Minutes				
Test Units	*DIS / T	25%	50%	75%
15 Cell Groups	-30°F	1 Group	1 Group	1 Group
10 Cells per Group	0°F	1 Group	1 Group	1 Group
150 Cells Total	+75°F	1 Group	1 Group	1 Group
		2 Batteries	2 Batteries	2 Batteries
20-Cell Batteries	+120°F	1 Group	1 Group	1 Group
6 Total	+140°F	1 Group	1 Group	1 Group

TABLE IV

SILVER-CADMIUM

Orbit 1 Period: 2 Hours
Charge: 85 Minutes
Discharge: 35 Minutes

Orbit 2 Period: 24 Hours
Charge: 22 Hours 48 Minutes
Discharge: 1 Hour 12 Minutes

Test Units	*DIS / T	25%		50%		75%	
		Orbit 1	Orbit 2	Orbit 1	Orbit 2	Orbit 1	Orbit 2
24 Cell Groups 8 Cells per Group	0°F	1 Group	1 Group	1 Group	1 Group	1 Group	1 Group
192 Cells Total	40°F	1 Group	1 Group	1 Group	1 Group	1 Group	1 Group
28-Volt Batteries	75°F	1 Group	1 Group	1 Group	1 Group	1 Group	1 Group
		1 Batt.	1 Batt.	1 Batt.	1 Batt.	1 Batt.	1 Batt.
6 Total	120°F	1 Group	1 Group	1 Group	1 Group	1 Group	1 Group

TABLE V

SILVER-ZINC

Orbit 1 Period: 2 Hours
Charge: 85 Minutes
Discharge: 35 Minutes

Orbit 2 Period: 24 Hours
Charge: 22 Hours 48 Minutes
Discharge: 1 Hour 12 Minutes

Test Units	*DIS / T	25%		50%		75%	
		Orbit 1	Orbit 2	Orbit 1	Orbit 2	Orbit 1	Orbit 2
24 Cell Groups	0°F	1 Group	1 Group	1 Group	1 Group	1 Group	1 Group
8 Cells per Group	40°F	1 Group	1 Group	1 Group	1 Group	1 Group	1 Group
192 Cells Total	75°F	1 Group	1 Group	1 Group	1 Group	1 Group	1 Group
		1 Batt.	1 Batt.	1 Batt.	1 Batt.	1 Batt.	1 Batt.
28-Volt Batteries 6 Total	120°F	1 Group	1 Group	1 Group	1 Group	1 Group	1 Group

SUMMARY OF LIFE-CYCLING TEST CONDITIONS

*DIS denotes cycling Depth of Discharge. T denotes Temperature.

V. BIBLIOGRAPHY

A. Knowlton, A. E. and others, "Standard Handbook for Electrical Engineers", 8th ed, York Pa., McGraw-Hill Book Company, Inc. 1949, 2311 pp.

B. Ryan, W. E. and others, "Final Test Report on Battery Power Supply Satellite Sonotone P/N W22398", Sonotone Corp., March 1960.

C. Vinal, G. W. "Storage Batteries", 4th ed, New York, John Wiley & Sons, Inc., 1955, 446 pp.

D. ------"Qualification Test Report on Battery Power Supply, Satellite Sonotone P/N W22398", Sonotone Corp., April 1960.

E. ------"Final Report on Study of Sealed Nickel-Cadmium Batteries December 1, 1958 to January 31, 1960", Contract No. DA-36-039-SC-78249, 1960.

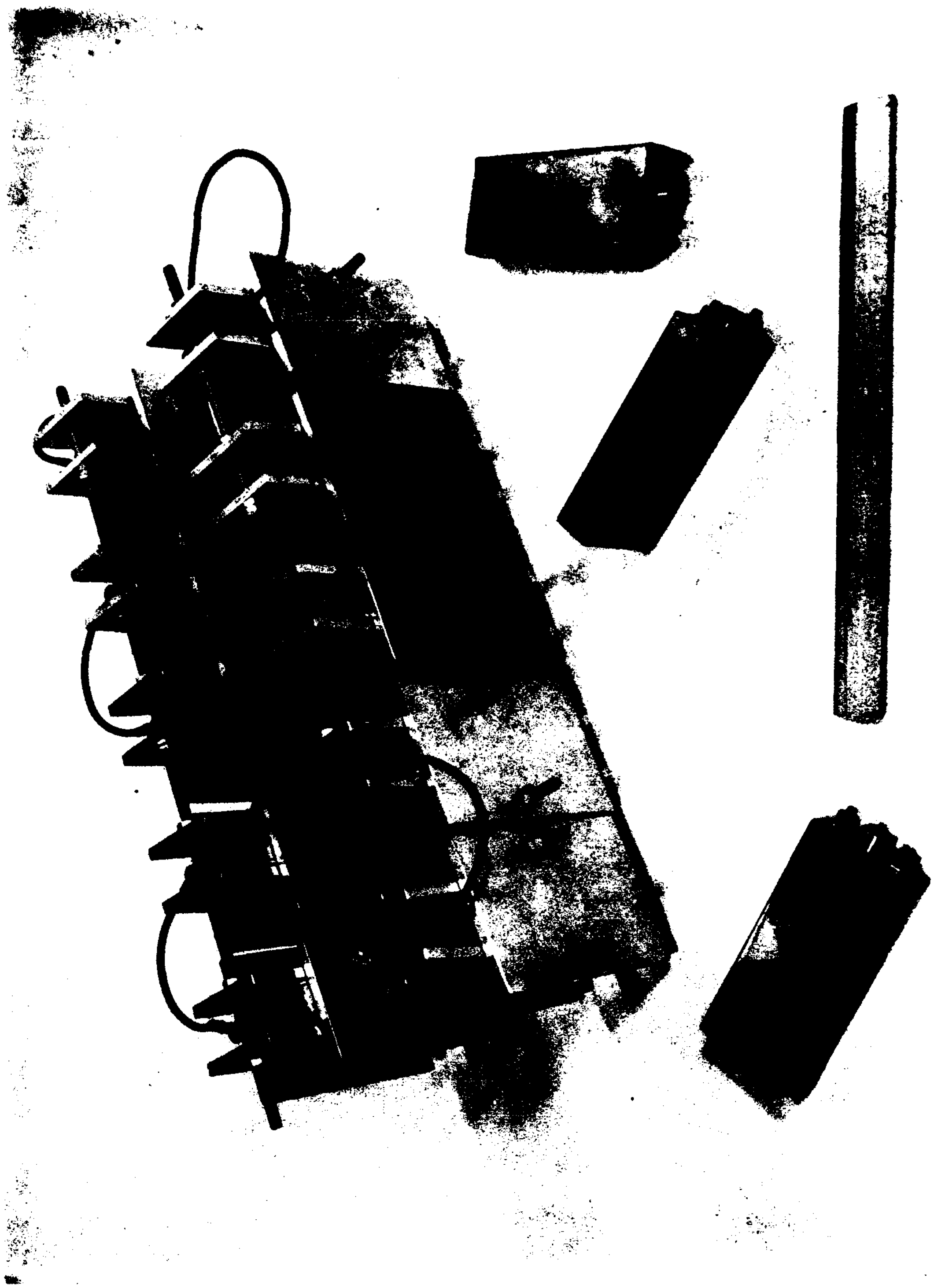

Figure 32 - Series-Connected Cell Group (10 cells) in a Restraining Fixture

Figure 35 - Nickel Cadminum 20-cell Battery with individual cell wires and three thermocouples

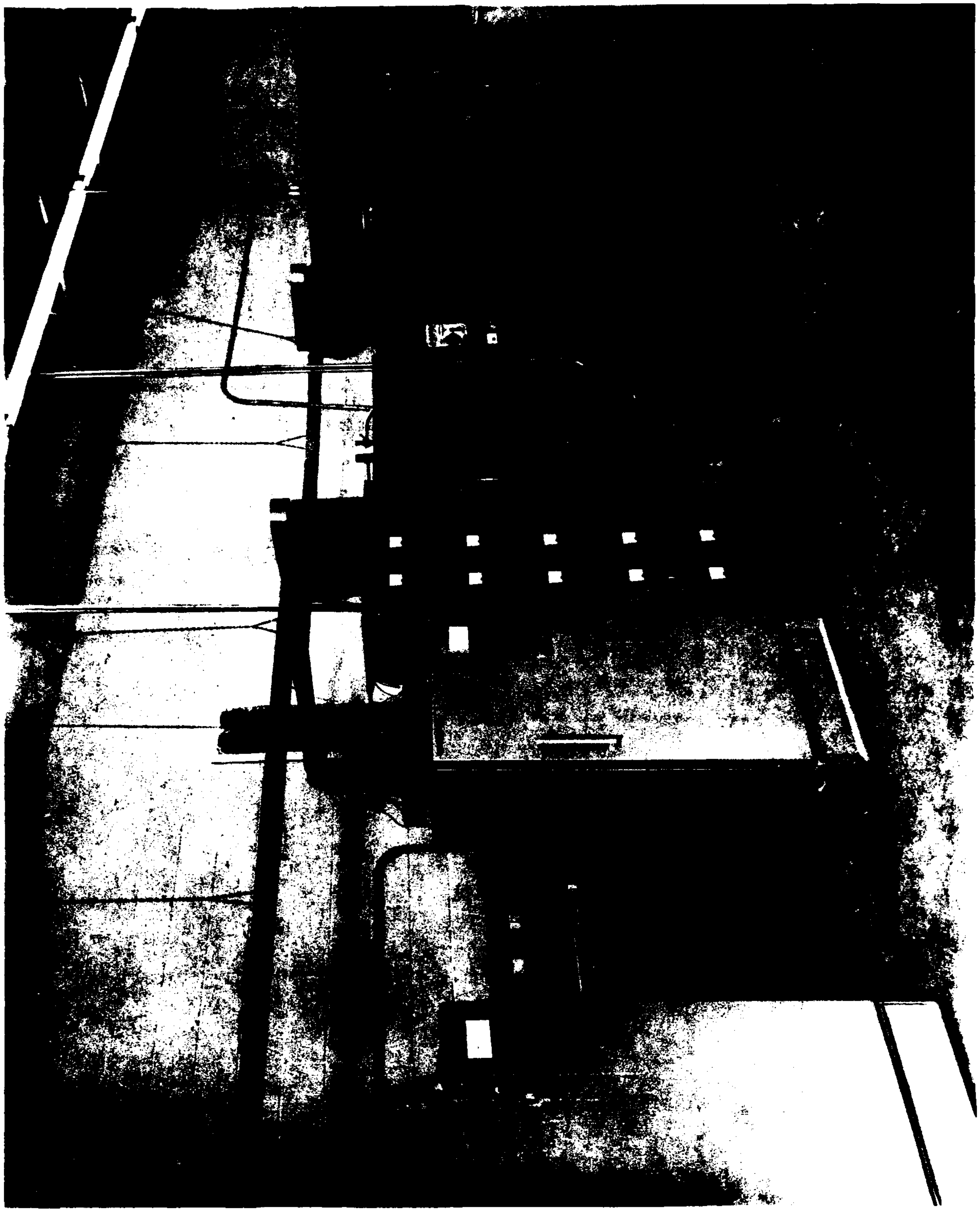

Figure 34 - Temperature Chambers and Charge/' ırge Equipment Racks

Figure 35 - Chamber with Cell Test Groups

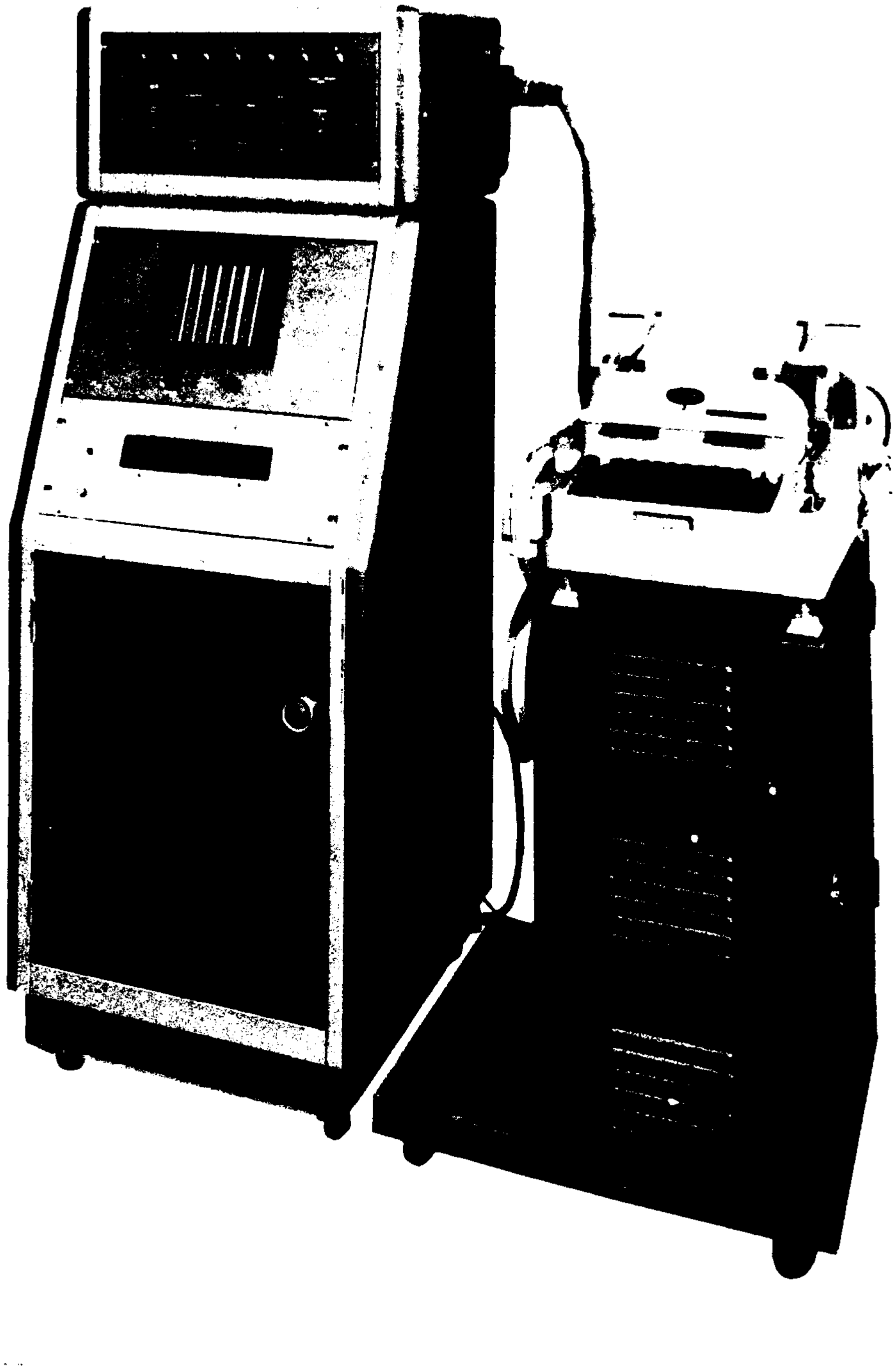

Figure 36 - Automatic Data Handling Consoles and Flexowriter

APPENDIX I

Procedure for Performance of Cell Failure Analysis by Manufacturers

I. A Preliminary Failure Analysis Report will be furnished to the manufacturer of each cell submitted for failure analysis.

II. Electrical and mechanical measurements and tests of the cells, shall be performed to determine the cause(s) of the cell failure. The tests shall be selected and performed so as to minimize additional deterioration of the cell. The tests shall also be sequenced such that each test shall have a minimum effect upon the results of all subsequent tests. All measurements and test results shall be recorded and made available.

III. Tests and inspections shall be performed to make the following analyses of internal parts and to determine the principal cause of the cell failure:

A. Electrolyte Analysis

1. Determine concentration (where feasible)
2. Quantity (where feasible)
3. Purity - Check for foreign materials and extent of impurities, especially the concentration of carbonate.
4. Concentration of active plate material dissolved in the electrolyte.
5. Other deterioration.

B. Separator Analysis

1. Determine degree of general deterioration
2. Remarks as to cause of deterioration, e.g. reaction with electrolyte, acceleration caused by heat, etc.
3. Reaction of separator with active material of the plates.
4. Determine extent of penetration of active materials into the separators.
5. Shorts

   a. Degree

   b. Location (at Tab-Plate Junction, etc.)

c. Cause

1. Metal particles
2. Foreign matter
3. Mechanical failure (Warping plates mashing through separator material, etc.)
4. Grid mesh puncture
5. Original positioning (of separators and plates)
6. Plastic breakdown(chemical or mechanical)

6. Capillary Action

a. Reduction from chemical changes, etc.

7. Other deterioration

C. Plate Analysis

1. Check for deformation, buckling, warping, etc.

a. Cause
b. Effects (shorting, reduced electrical contact, etc.)

2. Amount and composition of sludge in bottom of cell.
3. Determine erosion of plates or loss of active materials.
4. Condition of grids
5. Evidence of non-uniform current distribution
6. Adherence of sintered material and/or active material to grids.

D. Tab Analysis

1. Check for faulty tab-to-plate connections
2. Check for faulty tab-to-terminal connections
3. Check for tab corrosion
4. Other deterioration

E. Detailed Analysis of Case and Accessories (Seals, Valves, Terminals, etc.)

1. Case leakage
2. Case distortion

APPENDIX I

3. Seal Leakage
4. Relief Valve Operation
5. Terminals

IV. The analyses for cell failures shall be performed in accordance with military-accepted inspection and testing methods. The test apparatus used shall have sufficient accuracies to give valid determinations of the extent of cell component deterioration.

V. The extent or per cent of change in condition from the original design condition (for a cell of the same type) shall be reported for each of the components of IIIA, B, C, D, and E above.

VI. Upon completion of the failure analysis and after determination of the cause(s) of failure, recommendations for specific design changes and/or a research program to correct the cell failures shall be submitted with the failure analysis reports. Sufficient data to substantiate each recommendation made shall be furnished.

VII. Permission to witness any of the tests for failure analysis performed at the manufacturer's facilities, shall be granted to technical personnel of Inland Testing Laboratories or the United States Air Force.

APPENDIX I

ITL CELL NO. _____

ALKALINE BATTERY EVALUATION PROGRAM

Contract AF33(616)-7529

Preliminary Failure Analysis Report

1. Description of Cell:

   A. Mfr. ____________________ B. Type ____________________

   C. Capacity ____________________ D. Mfr. Model No. __________

2. Test Environment:

   A. Temperature ________ °F B. Group or Battery No. _____

3. Cycle Parameters:

   A. Cycle Period ____________

      1. Charge ______________ 2. Discharge ________________

   B. Cycle Voltage or Current for Cell Group or Battery

      1. Charge ______________ 2. Discharge ________________

   C. Depth of Discharge (Cycle Range in % of Full Charge). ______

4. Number of Cycles Completed ____________________

5. Date of Failure ________________________________

6. Visual Inspection for external evidence of the following:

	Yes	No	Remarks
A. Case leakage			
B. Case distortion			
C. Seal leakage			
D. Excessive heat			
E. Relief valve actuated			
F. Terminal damage			

7. Criteria for Terminating Test: ________________________________

   ____

8. Other Remarks: ____

   ____